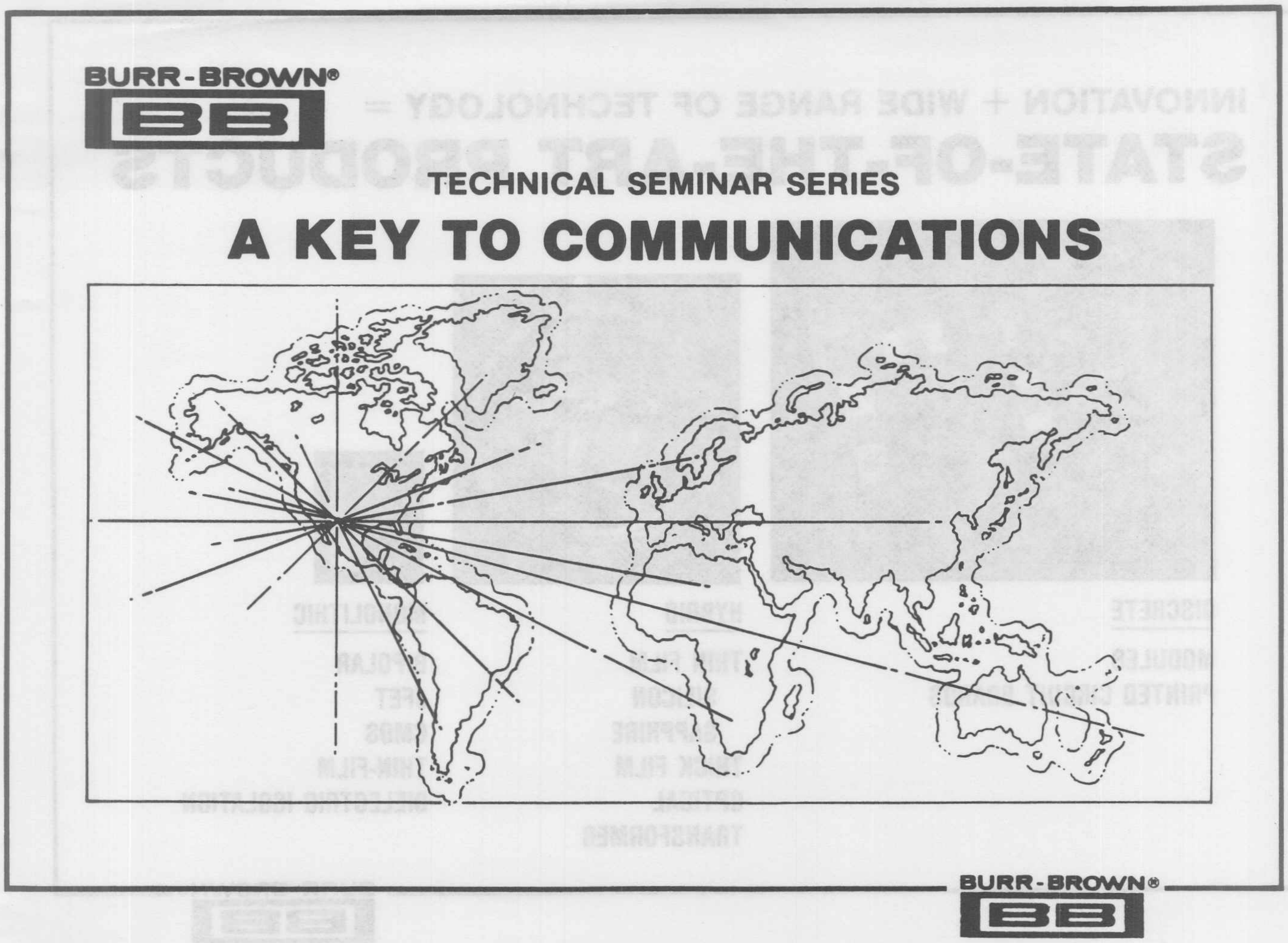


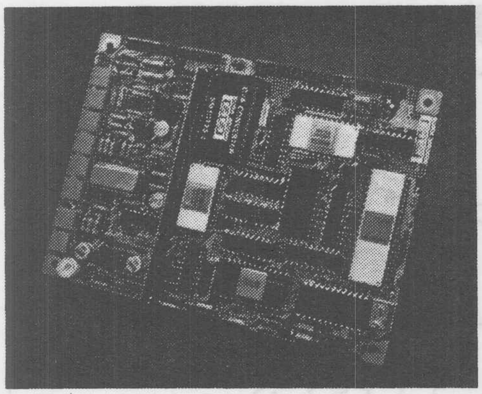
-1-

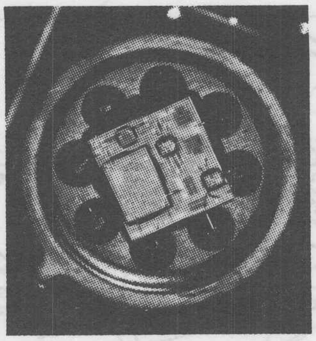
This is one of a continuing series of applications seminars presented around the world. It is designed to share with you circuit ideas, new products and technology advancements which can make your design and development efforts more productive.

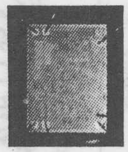
It is prepared by Burr-Brown staff engineers from their own ideas and from users of our products who have shared their creative designs with others.

INNOVATION + WIDE RANGE OF TECHNOLOGY =

STATE-OF-THE-ART PRODUCTS







DISCRETE

MODULES
PRINTED CIRCUIT BOARDS

HYBRID

THIN FILM
  SILICON
  SAPPHIRE
THICK FILM
OPTICAL
TRANSFORMER

MONOLITHIC

BIPOLAR
JFET
CMOS
THIN-FILM
DIELECTRIC ISOLATION

BURR-BROWN®

Burr-Brown has a wide variety of technologies and products available providing solutions to design and instrumentation problems. This seminar focuses on integrated circuit components... both hybrid and monolithic.

Within the integrated circuit arena, Burr-Brown has pioneered many processes and techniques which make possible the high performance of our products.

INA 115
41 VOLT INPUT
INSTR. AMP.

Operational Amplifiers For High Performance Applications.

BURR-BROWN®

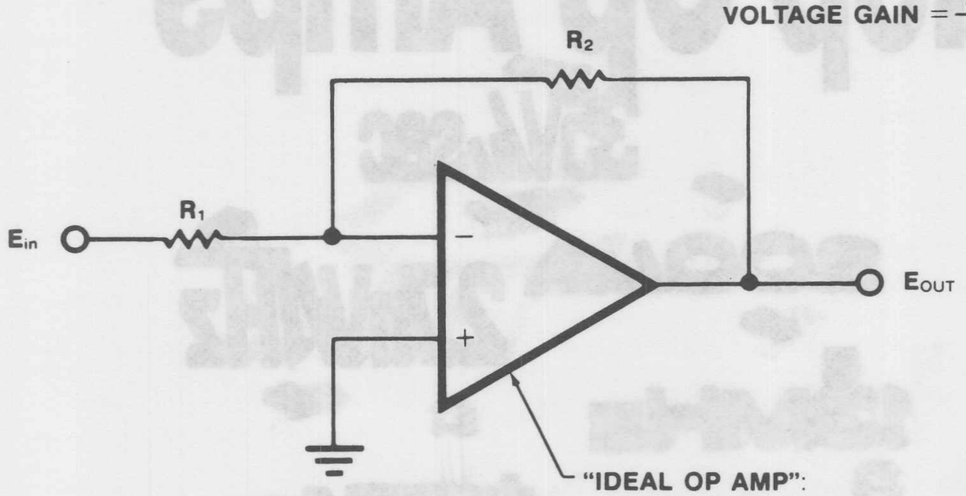
-3-

The operational amplifier has made a tremendous impact on circuit design technique. The simplification and versatility of op amps has improved system performance, allowed more compact systems, and simplified the design process.

Since the introduction of the first commercially available transistorized laboratory amplifier in 1956, Burr-Brown has been a leader in op amp technology. Burr-Brown continues that leadership with devices such as the OPA111, widely accepted as the best precision op amp available.

INVERTING AMPLIFIER

$$\text{VOLTAGE GAIN} = \frac{E_{OUT}}{E_{in}} = \frac{-R_2}{R_1}$$



"IDEAL OP AMP":

OPEN LOOP GAIN:	$A_{VS} = \infty$
INPUT OFFSET VOLTAGE:	$V_{IO} = 0$
INPUT BIAS CURRENT:	$I_B = 0$
NOISE, e_n and i_n:	$= 0$

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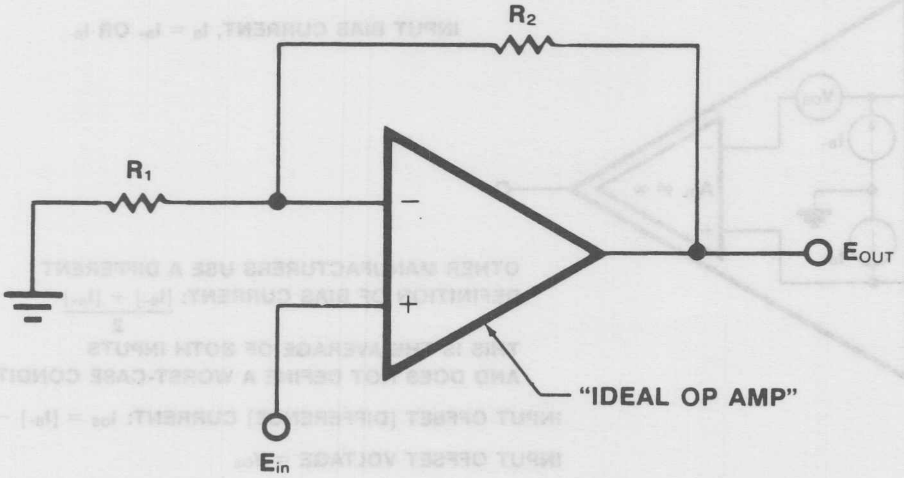
The "ideal op amp" assumption allows a basic understanding of the common op amp configurations. Since an op amp is assumed to possess infinite gain, it requires a vanishingly small differential input voltage to create any output voltage. This implies that the inverting input has no signal voltage and can be considered a "virtual ground" during linear operation. The input voltage will then create an input current equal to Ein/R1.

Since no input current flows in the op amp's inputs (infinite input impedance), all input current flowing in R1 is forced to flow through the feedback resistor, R2. With one side of R2 established at virtual ground and a known current flowing through it, the output voltage is defined as -Ein*R2/R1. Or, stated as a voltage gain--

Av = -R2/R1

NONINVERTING AMPLIFIER

$$\text{VOLTAGE GAIN} = \frac{E_{OUT}}{E_{in}} = 1 + \frac{R_2}{R_1}$$



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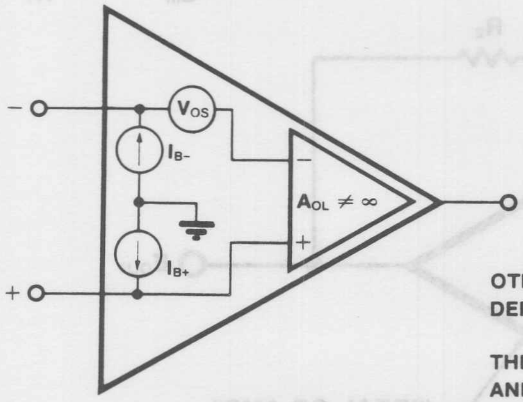
Since zero differential input voltage is required for any output voltage, an input applied directly to the noninverting op amp terminal causes the inverting input to follow. The resulting current flowing in R1 (due to the input voltage being impressed across it) also must flow in R2. The output voltage is comprised of the sum of Ein (across R1) and the voltage across R2. The voltage across R2 is equal to the current (Ein/R1) times R2. The output voltage is then--

$$\begin{aligned} Eout &= Ein + (Ein^*R2/R1) \\ &= Ein^*(1 + R2/R1) \end{aligned}$$

Or, stated as a voltage gain--

$$Av = 1 + (R2/R1)$$

NON-IDEAL OP AMP



INPUT BIAS CURRENT, $I_B = I_{B+}$ OR I_{B-}

OTHER MANUFACTURERS USE A DIFFERENT DEFINITION OF BIAS CURRENT: $\frac{[I_{B-}] + [I_{B+}]}{2}$

THIS IS THE AVERAGE OF BOTH INPUTS AND DOES NOT DEFINE A WORST-CASE CONDITION

INPUT OFFSET [DIFFERENCE] CURRENT: $I_{OS} = [I_{B-}] - [I_{B+}]$

INPUT OFFSET VOLTAGE = V_{OS}

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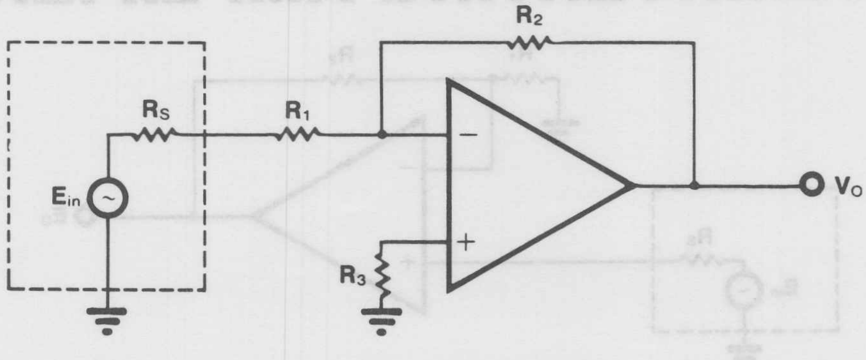
Deviation from the ideal op amp model includes, among others, input offset voltage and bias current, and finite open loop gain. Depending on the application, the assumptions of the ideal op amp may range from entirely adequate to frustratingly misleading. Good design includes an evaluation of the errors created by the less-than-ideal op amp in the desired configuration. High performance design often involves searching for circuit configurations which minimize the adverse affects of deviations from the ideal and careful selection of high performance op amps to reduce errors.

Be aware that not all manufacturers specify op amps in the same manner. For instance, many manufacturers specify bias current as the average of the two input currents. Burr-Brown specifies the worst case bias current in each input. Manufacturers of low performance FET op amps specify bias current at 25'C junction temperature. Bias current is significantly higher after the amplifier is warmed up at 25'C ambient temperature.

DC ERROR CALCULATIONS INVERTING AMPLIFIER



$$\text{OFFSET AT OUTPUT} = V_{OS}\left(1+\frac{R_2}{R_1+R_S}\right) + (I_{B-})R_2 - (I_{B+})R_3\left(1+\frac{R_2}{R_1+R_S}\right)$$

$$\text{OFFSET AT OUTPUT} = V_{OS}\left(1+\frac{R_2}{R_1}\right) + (I_{OS})R_2; \quad \text{if } R_3 = \frac{R_1R_2}{R_1+R_2} \text{ and } R_S = 0$$

$$\text{GAIN} = \frac{-R_2}{R_1+R_S}\left[\frac{1}{1+\frac{1}{A_{OL}}\left(1+\frac{R_2}{R_1+R_S}\right)}\right]$$

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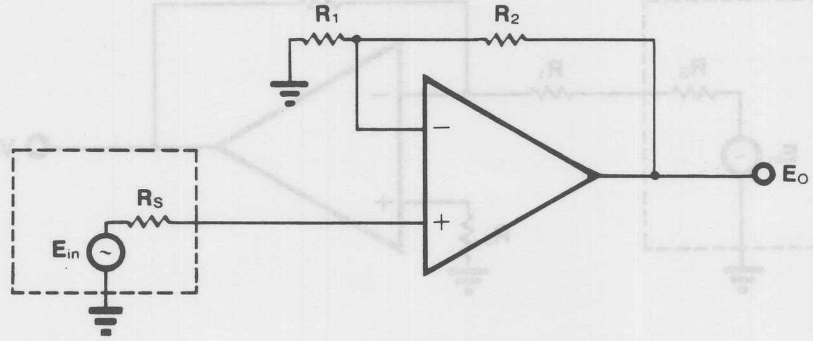
Balancing the source impedances seen by the two op amp inputs removes the influence of input bias current on output voltage offset errors. The remaining offset is due the input offset voltage and the difference of the two bias currents (input offset current).

Note that the offset voltage in inverting unity gain is twice the input offset voltage of the op amp (plus the input offset current term). Although the closed loop gain with equal R1 and R2 is inverting unity, the "noise gain" is one plus the gain (ignoring the sign) or two. Errors such as offset and noise are multiplied by the noise gain of the configuration.

Deviation of the actual gain from the predicted gain can become significant if high closed loop gain is required.

DC ERROR CALCULATIONS NONINVERTING AMPLIFIER



$$\text{OFFSET AT OUTPUT} = V_{OS}\left(1+\frac{R_2}{R_1}\right) + (I_{B-})R_2 - (I_{B+})(R_S + R_3)\left(1+\frac{R_2}{R_1}\right)$$

$$\text{OFFSET AT OUTPUT} = V_{OS}\left(1+\frac{R_2}{R_1}\right) + (I_{OS})R_2; \quad \text{if } R_3 + R_S = \frac{R_1R_2}{R_1+R_2}$$

$$\text{GAIN} = 1+\frac{R_2}{R_1}\left[\frac{1 \pm \dfrac{1}{\text{CMRR}}}{1+\dfrac{1}{A_{OL}}\left(1+\dfrac{R_2}{R_1}\right)}\right]$$

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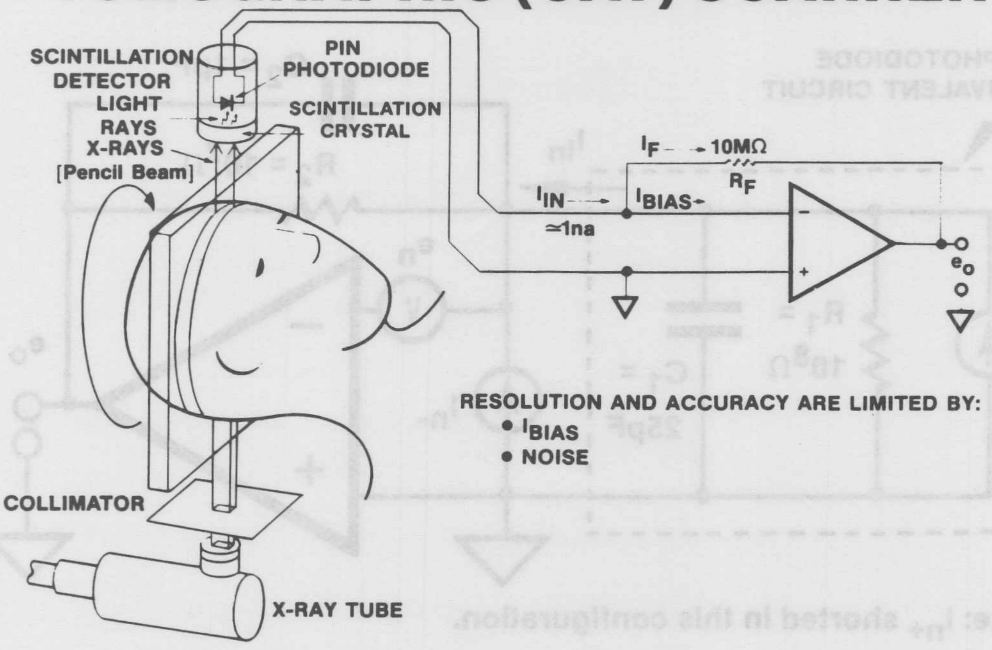
The noninverting gain circuit eliminates the gain error associated with loading of the source impedance, Rs, by providing a very high input impedance. As with the inverting amplifier, gain is influenced by the open loop gain of the amplifier. This is often the dominant source of gain error in high gain circuits or at high frequencies where the open loop gain is diminished.

Another effect contributes to gain error in this configuration. Since the input voltage is applied directly to one of the op amp's inputs, the common mode voltage of the op amp is changing. As a result, there is an error term associated with the common-mode rejection of the op amp. CMRR errors may be the dominant gain and linearity error source in the noninverting amplifier in low gain/low frequency applications.

COMPUTERIZED AXIAL TOMOGRAPHIC (CAT) SCANNER



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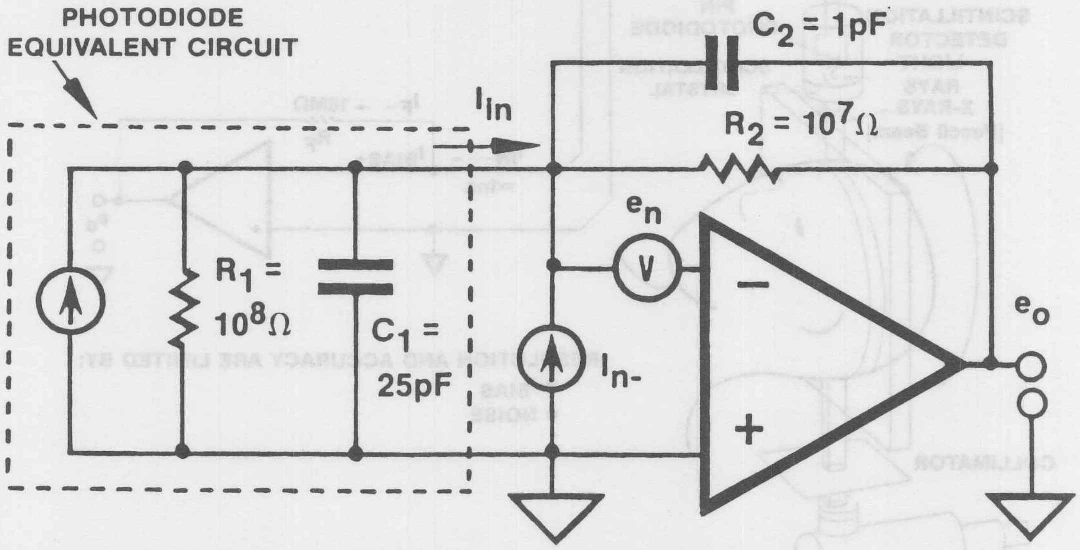
-9-

A "CAT" scanner application provides a demanding and informative circuit example:

A photodiode is used as an optical sensor and must be amplified by a low noise circuit. The photodiode's output is a current which is proportional to its optical excitation, thus the op amp is configured as a current-to-voltage converter or transimpedance amplifier.

Due to the high source impedance and very low signal currents of the photodiode, a low input bias current amplifier is required. Noise performance of the op amp is also an important concern.

NOISE MODEL OF PHOTO DIODE APPLICATION



Note: i_{n+} shorted in this configuration.

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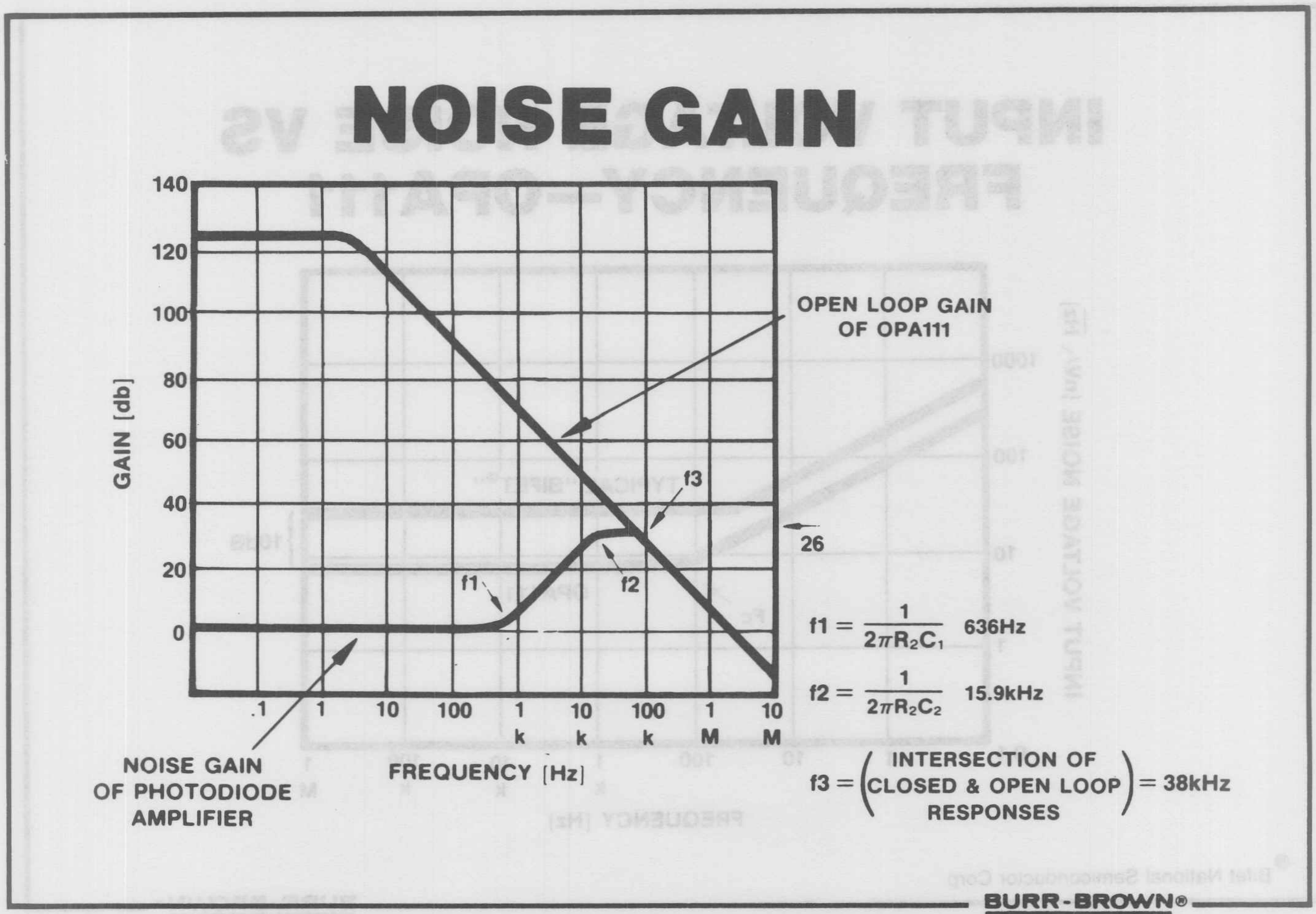
In this noise model of the previous circuit, R1 and C1 characterize the source impedance of the photodiode. C2 is the stray capacitance of the feedback resistor, R2. The op amp's noise is modeled by its noise current, In, in parallel with each input and a voltage noise, En, in series with either the input terminal. Since the noninverting input (and its corresponding noise current source) is grounded, only one of the noise current sources contributes to the total noise.

The total input noise is the rms sum of the op amp's voltage noise and its current noise reacting with the total impedance at the input terminal. The output noise is equal to the total input noise times the "noise gain."

The noise gain of the circuit is Avn = 1+(Zf/Zi). C1 plays a critical role in the noise performance of the circuit since it is the dominant part of Zi. C1's decreasing impedance with frequency causes the noise gain to increase with frequency.



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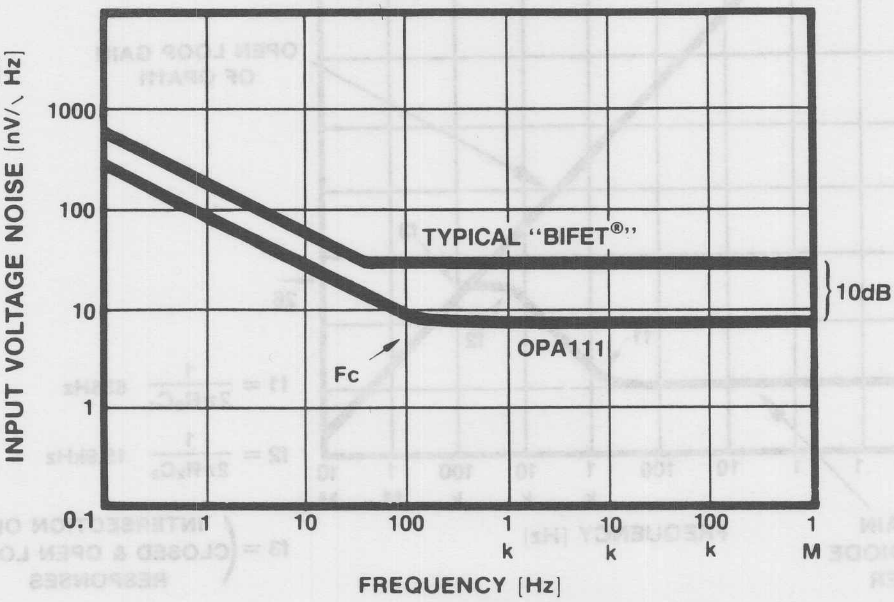
At low frequency, the noise gain is equal to the noninverting gain set by the resistors-- 1 + R2/R1 = 1.1, or approximately 0 dB. The noise gain rises at 20 dB/decade at the corner frequency f1 where the C1's reactance equals R2. (The decreasing reactance of C1 increases the gain as a function of frequency.)

As the reactance of C2 decreases and dominates the feedback impedance, the noise gain becomes flat with frequency at a gain equal to 1 + C1/C2. The circuit's high frequency noise gain is eventually limited by the open loop gain of the amplifier which rolls off at 20 dB/decade. The composite noise gain response has a large peaked region from 10kHz to 100KHz that dominates the total noise performance. Note that the root cause of this peak is C1's effect on the noise gain (a reason to search low capacitance photodiodes).

INPUT VOLTAGE NOISE VS FREQUENCY—OPA111



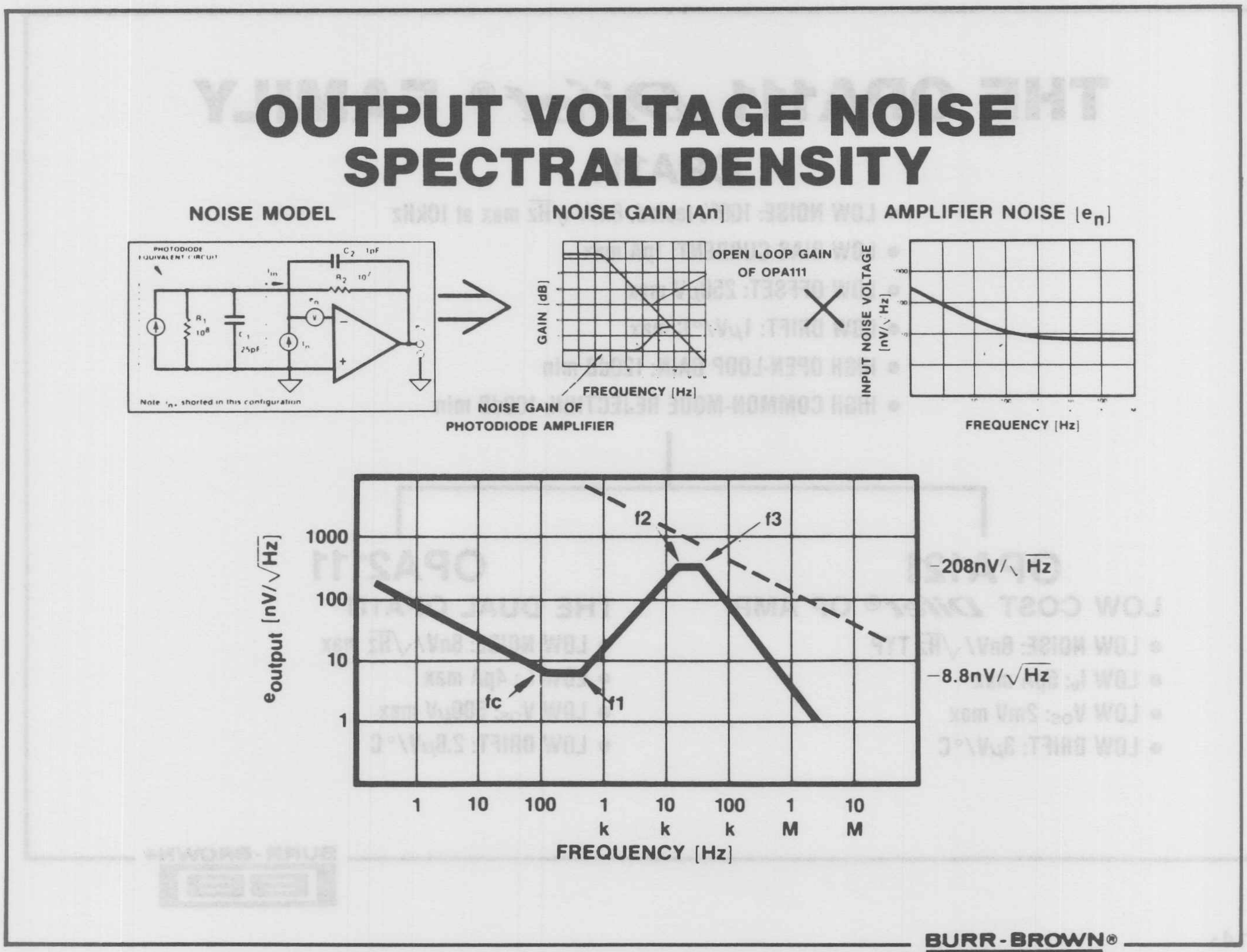
® Bifet National Semiconductor Corp.

BURR-BROWN®

The major source of noise in this example is the op amp's voltage noise. The OPA111's voltage noise spectral density assumes the classical shape with a flat high frequency region and a rising 1/f low frequency region. The 1/f region has a slope of -10 dB/decade.

Voltage noise performance of the OPA111 is truly exceptional with a 100% tested and guaranteed 8 nV/(root–Hz) flat band noise.

Although some manufacturers boast of a very low corner frequency, fc, this can be deceiving. A noisy flat band region, for instance, creates a low corner frequency! Compare noise specifications carefully.



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The resulting output noise spectral density is a combination of the circuit's noise gain and the 1/f characteristic of the op amp.

In many applications the total output noise is the major concern. To determine the most important region contributing to the total noise, draw a line at a -10 dB/decade slope above the spectral density plot (dotted line) and visualize it sliding downward. The first region it would touch on the spectral density plot is the dominant region. This leads to the conclusion that the photodiode capacitance (C1) creating the rising noise gain, presents a limiting factor in noise performance of this circuit.

THE OPA111 *Difet*® FAMILY

OPA111

- LOW NOISE: 100% tested, 8nV/$\sqrt{Hz}$ max at 10kHz
- LOW BIAS CURRENT: 1pA max
- LOW OFFSET: 250μV max
- LOW DRIFT: 1μV/°C max
- HIGH OPEN-LOOP GAIN: 120dB min
- HIGH COMMON-MODE REJECTION: 100dB min

OPA121

LOW COST *Difet*® OP AMP

- LOW NOISE: 6nV/$\sqrt{Hz}$ TYP
- LOW I_b: 5pA max
- LOW V_{OS}: 2mV max
- LOW DRIFT: 3μV/°C

OPA2111

THE DUAL OPA111

- LOW NOISE: 8nV/$\sqrt{Hz}$ max
- LOW I_b: 4pA max
- LOW V_{OS}: 500μV max
- LOW DRIFT: 2.8μV/°C

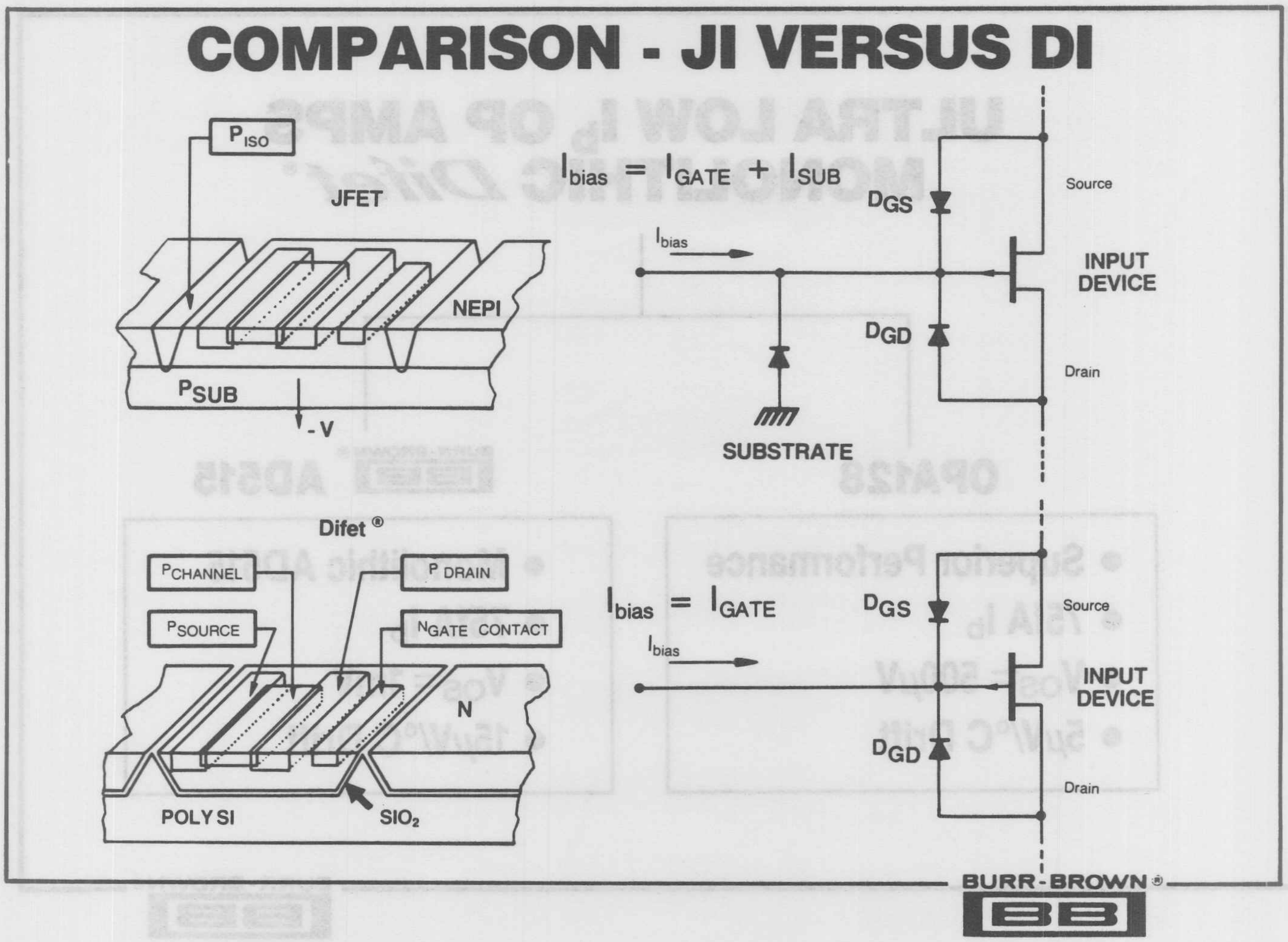
BURR-BROWN®

The wide acceptance of the OPA111 Difet amplifier has led to the development of two related op amps--the OPA2111 dual Difet, and the OPA121 low cost Difet. The OPA2111 brings near '111 performance with the cost and space savings of two amplifiers in one package. The OPA121 has somewhat reduced specification for cost sensitive applications. (Compare its "reduced" specs to other FET op amps!)

Difet (dielectric isolated FET) fabrication is much more than a "buzz word". Dielectric isolation eliminates the diode junction which is otherwise used to isolate one monolithic transistor from the next. Large diode junctions which result when FET transistors are fabricated have parasitic leakage currents which greatly degrade bias current performance. By isolating each transistor from the next with a true insulating material, important performance benefits are achieved.

When combined with advanced circuit topology, including new low-noise cascoded input stage techniques, the OPA111 family achieves performance well beyond that attainable with conventional BIFET(R) technology.

Difet(R) Burr-Brown Corp.
BIFET(R) National Semiconductor Corp.



With Junction Isolated (JI) integrated circuits, interaction of individual components is prevented with a reverse-biased diode junction. The resulting large parasitic diode junction from the gates of the input FETs to the substrate produces correspondingly large leakage currents.

The extremely low input bias current of the OPA111 owes to its use of the Dielectric Isolation (DI) process. Individual monolithic components are insulated from adjacent devices with "motes" of Silicon Dioxide--an excellent insulator. This allows use of large input FET geometry without the severe compromise of degraded input bias current performance.

ULTRA LOW I_b OP AMPS
MONOLITHIC *Difet*®

OPA128

- Superior Performance
- 75fA I_b
- V_{OS}= 500μV
- 5μV/°C Drift

BURR-BROWN® BB **AD515**

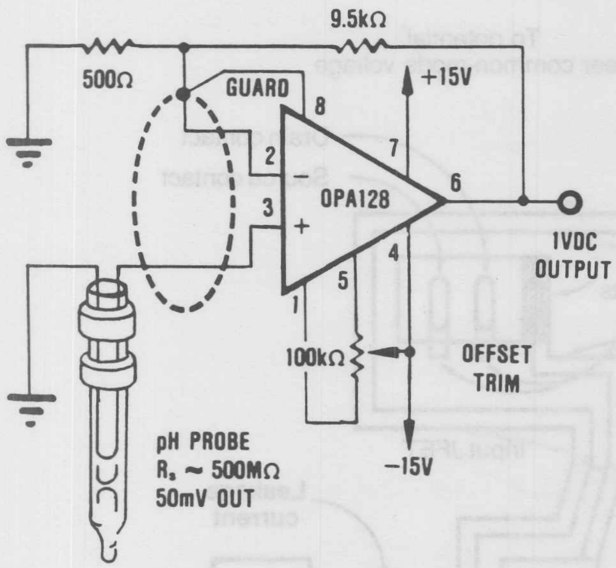
- Monolithic AD515
- 75fA I_b
- V_{OS}= 1mV
- 15μV/°C Drift

BURR-BROWN® BB

The OPA128 achieves 75 fA input bias current performance using monolithic technology. Furthermore, it surpasses the performance of other devices using more expensive hybrid technology. Its offset voltage of 500 uV and offset drift of 5 uV/C surpasses the AD515.

Burr-Brown has also provided an AD515 gradeout of this part meeting all specifications of the AD515 for existing applications. Performance can be easily upgraded by selecting the pin compatible OPA128.

75fA I_b WITH A MONOLITHIC OP AMP!



OPA128

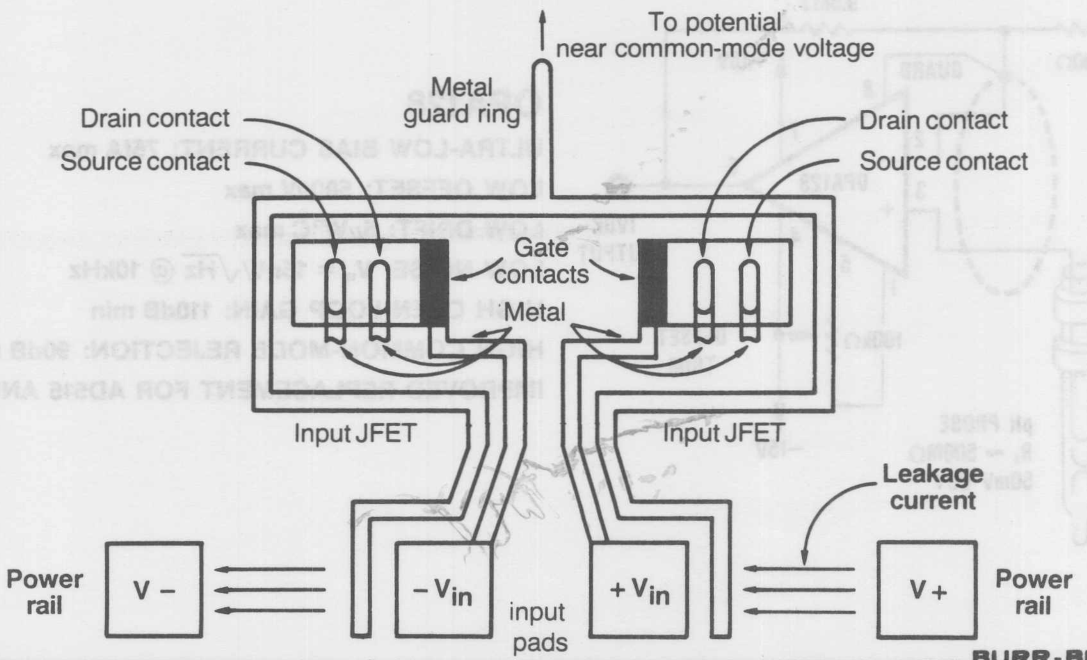
- ULTRA-LOW BIAS CURRENT: 75fA max
- LOW OFFSET: 500μV max
- LOW DRIFT: 5μV/°C max
- LOW NOISE: $V_n = 15nV/\sqrt{Hz}$ @ 10kHz
- HIGH OPEN-LOOP GAIN: 110dB min
- HIGH COMMON-MODE REJECTION: 90dB min
- IMPROVED REPLACEMENT FOR AD515 AND AD549

BURR-BROWN®

Certain extremely high impedance sensors such as pH probes require amplification of low-level output signals. These applications have previously required more costly op amps using hybrid construction techniques. Now, electrometer amplifier performance is available in a monolithic op amp.

Here, a pH probe is amplified by a gain of 20. It is a demanding circuit application because of the importance of input bias current and offset voltage and drift. The source impedance is approximately 500 Mohms!

ON CHIP GUARDING PREVENTS Ib DEGRADATION FROM SURFACE LEAKAGE



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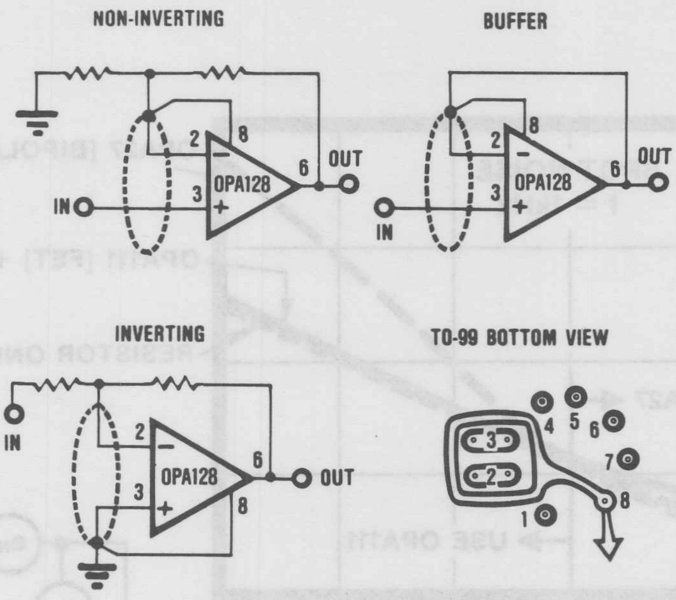
Major sources of gate current leakage including diode junction isolation leakage have been eliminated by dielectric isolation. Residual effects then become the predominate component of input bias current:

A key to the low input bias current performance of the OPA128 is its careful attention to these residual effects including guarding of surface leakage. Guard metal traces which are maintained at potentials nearly equal to that of the input gates encircle the critical gate connections. Particular attention is given to potential leakage paths from the nearby power supply connections since these represent worst case points from which leakage could emanate.

INPUT GUARDING AND LAYOUT



Guard top and bottom of board.
Alternate: use Teflon® standoff
for sensitive input pins.

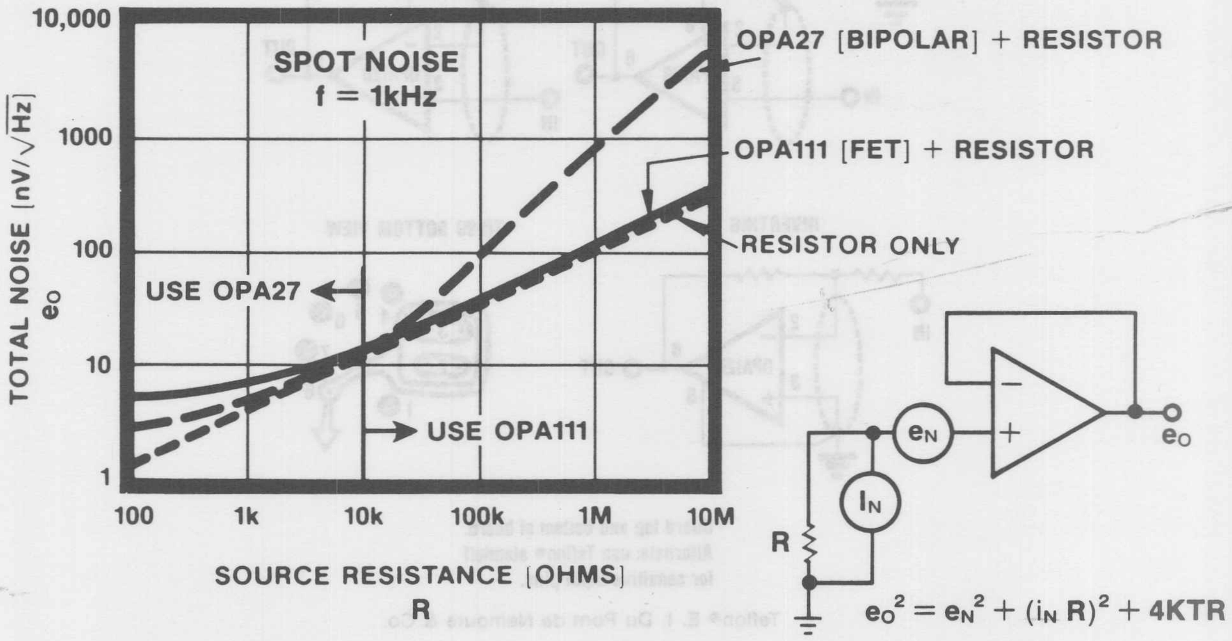
Teflon® E. I. Du Pont de Nemours & Co.

BURR-BROWN®

The superior input bias current characteristics of the OPA111 and OPA128's dielectrically isolated FETs can only be fully realized with careful attention to input guarding techniques. By encircling the critical high impedance node with a guard ring connected to a low impedance node at the same potential, errors caused by circuit board leakage currents can be minimized.

Surface contamination, improper circuit board cleaning processes and solder resist masks may also be culprits in degrading ultra-low bias current performance... especially at high temperature. Use of Teflon standoffs on critical nodes is yet another alternative in demanding applications.

NOISE—BIPOLAR VS FETS



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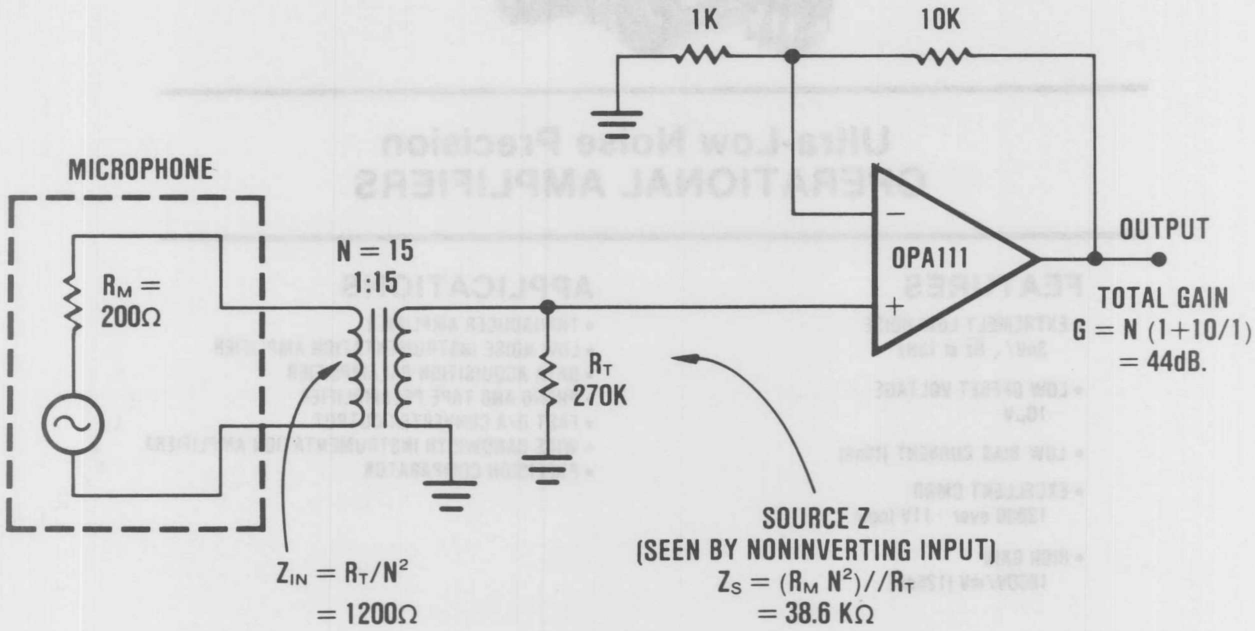
To achieve optimum noise performance (and DC accuracy too), choose the correct op amp. For source impedances less than 10k ohm, the OPA27's lower voltage noise and offset voltage due to its bipolar input will provide better overall performance. Above a 10k ohm source impedance, the OPA111's FET input with its far lower current noise will provide superior performance. Focusing only on the amplifier's voltage noise specification may lead to an inappropriate choice.

SOURCE Z:

LESS THAN 10k ohm ----> OPA27 BIPOLAR OP AMP

MORE THAN 10k ohm ----> OPA111 FET OP AMP

LOW NOISE PROFESSIONAL MICROPHONE AMPLIFIER



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By transforming a source impedance to a more favorable value, system noise performance can be dramatically improved. For example, professional microphones have source impedances ranging from 50 to 250 ohms, which is well below the OPA27's optimum source impedance.

The transformer increases the source impedance by a factor equal to the square of its turns ratio. Now the op amp "sees" a source impedance in the range where it contributes little additional noise. The very wide range of impedance (10k ohm to 2G ohm) over which the OPA111 provides a very low noise figure allows great flexibility in the choice of transformers and accommodates large variations in microphone impedance.

The transformer should not be viewed as "free gain" as it improves the noise performance only if the resulting impedance is in a favorable range for the amplifier. Use of this same 1:15 transformer with the OPA27, for instance, would produce inferior performance. If the OPA27 were chosen, the optimum source impedance would be approximately 10 kohms--equal to the noise voltage divided by the noise current.

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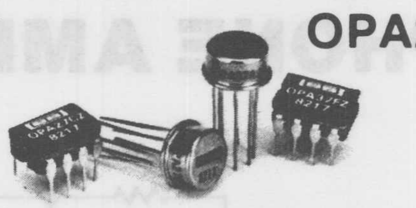
OPA27/OPA37



Ultra-Low Noise Precision OPERATIONAL AMPLIFIERS

FEATURES

- EXTREMELY LOW NOISE
  $3nV/\sqrt{Hz}$ at 1kHz
- LOW OFFSET VOLTAGE
  $10\mu V$
- LOW BIAS CURRENT (10nA)
- EXCELLENT CMRR
  126dB over ±11V Input
- HIGH GAIN
  1800V/mV (125dB)

APPLICATIONS

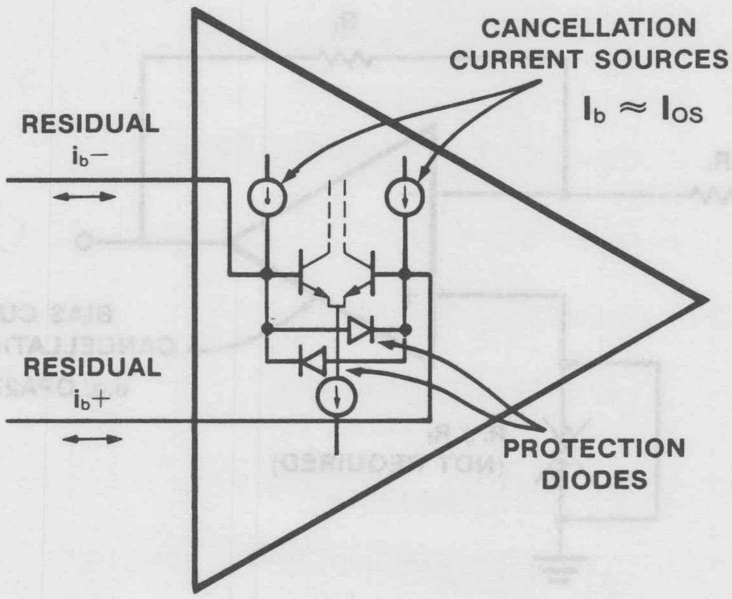
- TRANSDUCER AMPLIFIER
- LOW NOISE INSTRUMENTATION AMPLIFIER
- DATA ACQUISITION PREAMPLIFIER
- PHONO AND TAPE PREAMPLIFIER
- FAST D/A CONVERTER OUTPUT
- WIDE BANDWIDTH INSTRUMENTATION AMPLIFIERS
- PRECISION COMPARATOR

BURR-BROWN®

The OPA27 is a second source for the industry standard OP-27 op amp which has become a very popular part. Its very low voltage noise and precision DC offset and offset drift performance make it attractive in a wide variety of instrumentation applications.

In addition to offering a second source (at attractive prices), the OPA27 and OPA37 provides improved performance in a number of areas including bias current at high temperature and frequency stability. (If you have had oscillation problems with other manufacturers' parts, try ours... you'll like it.)

BIAS CURRENT CANCELLATION



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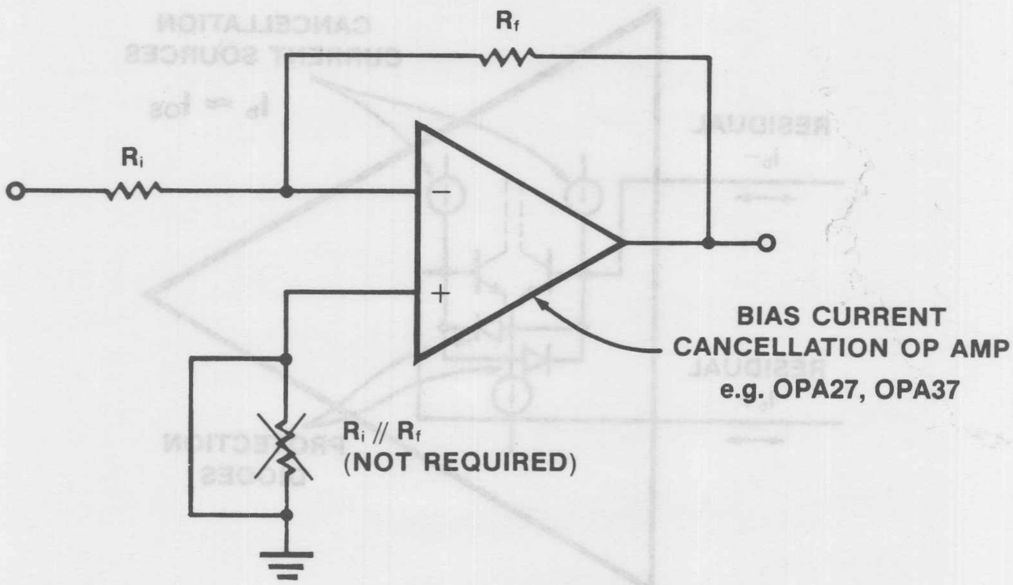
The OPA27 uses bias current cancellation to achieve its low input bias current performance. This allows relatively high currents to be used in the input transistor pair to achieve low noise and offset voltage. Cancellation current sources closely mirror the base current of the input pair making the residual bias current seen at the input terminals quite low. This results in the input offset current, Ios, being nearly the same magnitude as the input bias current. Also the residual input bias current could be positive or negative. These serve as tipoffs that a given op amp uses bias current cancellation.

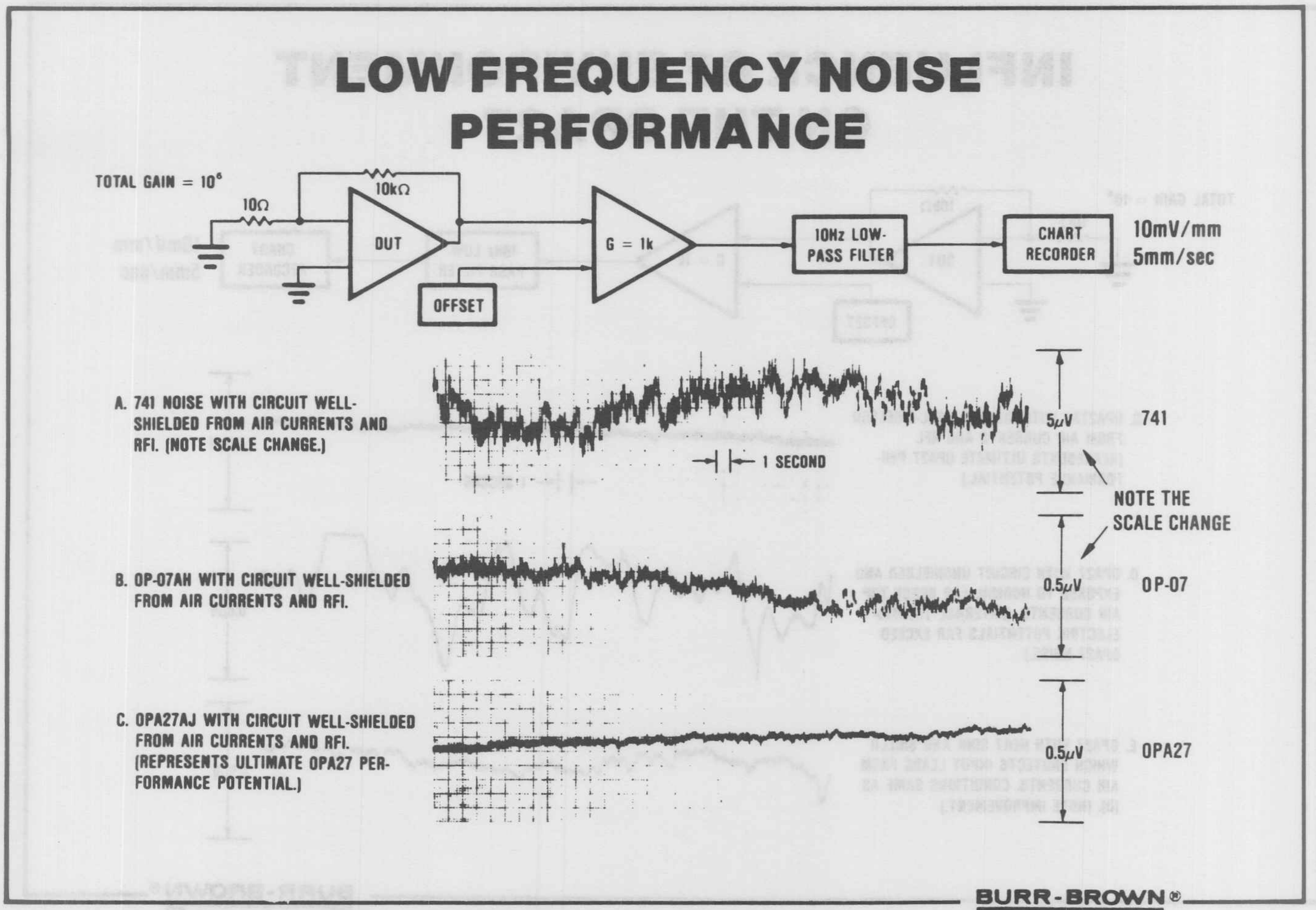
Protection diodes across the input terminals of the OPA27,37 (and other industry standard OP-27s as well) may affect operation in some circuits. When the op amp feedback loop is not in balance, such as during slewing, large input currents may flow in the protection diodes which can alter the expected results.

EQUAL INPUT IMPEDANCES NOT NEEDED



With an uncanceled input stage such as the 741, the nearly equal input bias currents implore the use of equal source impedances at the two inputs. The resulting equal offset voltages created by the two input currents can then be rejected as a common-mode voltage.

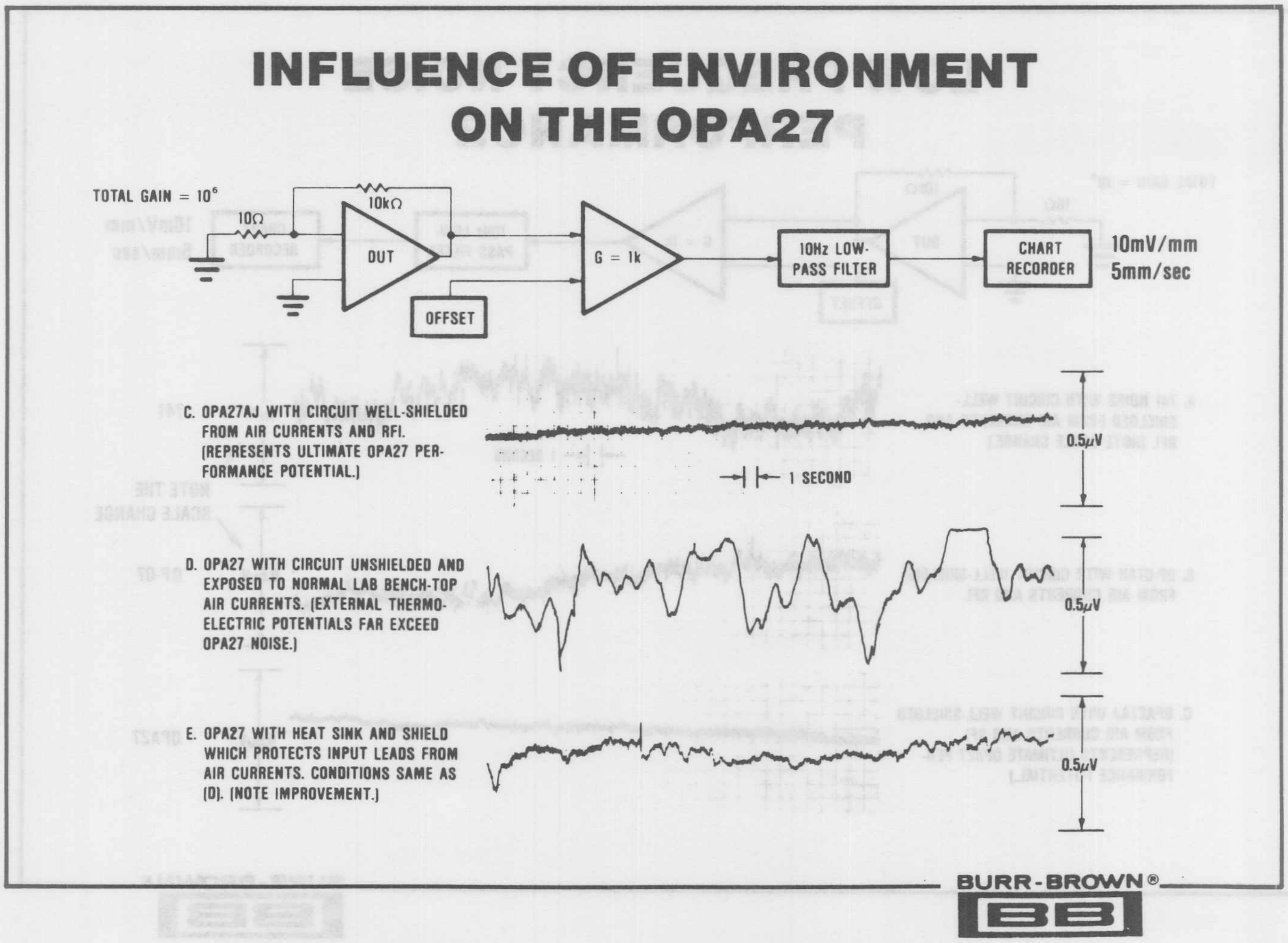
With the bias current canceled op amp such as the OPA27, the two input bias currents have been made as near zero as possible and statistically, no improvement will be achieved by equalizing the source impedances. In fact the addition of the resistor in the noninverting input is often counter-productive since the noise current associated with that input creates a voltage noise which is amplified at the output.



BURR-BROWN®

The OPA27's claim to fame is its low voltage noise, low offset voltage and drift. Here, Burr-Brown's high performance OPA27 is compared to the "741" and OP-07 op amps on a strip chart recorder. Note that if plotted to the same scale, the 741's noise would be off-scale.

The OPA27 improves on the industry standard OP-27 performance in many areas including high temperature bias current, typical noise, phase margin, power supply rejection, and output drive characteristics.

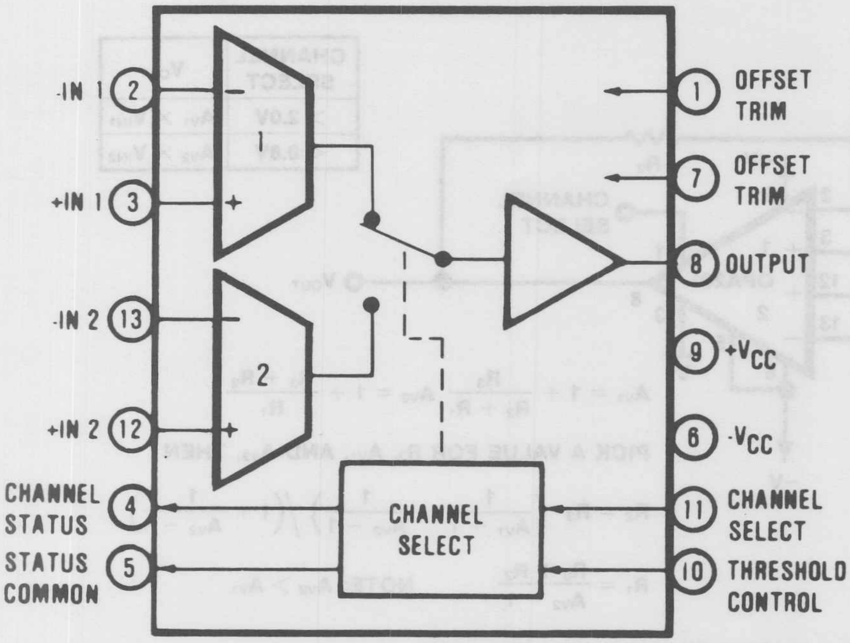


-26-

Physical environment makes a difference! The same OPA27 is shown in three mounting and packaging situations with dramatically different results. The high performance of the OPA27 is easily masked by low frequency noise generated by tiny thermal gradients in the input circuit leads and package (thermocouple effects). If strong air currents are unavoidable, a clip-on type heat sink and a "skirt" (model 0807HS) to shield the leads from direct air currents yields a large improvement in offset stability (very low frequency noise).

The vertical scale of the strip chart is extremely sensitive (0.5 uV full scale!) in these plots. The OPA27 is no more sensitive to thermally generated offset and noise than other amplifiers. Rather, its own noise is so low that effects which are normally "lost in the noise" are now made apparent.

OPA201 SWOP AMP™



FEATURES

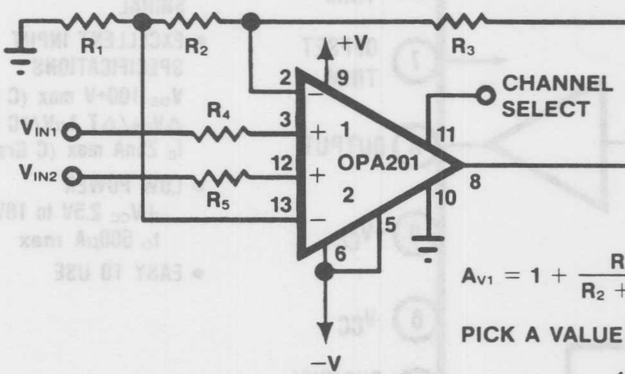
- TWO PRECISION INPUT STAGES SELECTABLE WITH CONTROL SIGNAL
- EXCELLENT INPUT SPECIFICATIONS
  V_{OS} 100+V max (C Grade)
  $\Delta V_{OS}/\Delta T$ 1μV/°C max (C Grade)
  I_B 25nA max (C Grade)
- LOW POWER
  $+V_{CC}$ 2.5V to 18V
  I_Q 500μA max
- EASY TO USE

BURR-BROWN®

The switchable input op amp or SWOP AMP is a unique component which is able to achieve a wide variety of signal switching functions. Its two input stages are steered to a single output stage by logic control. The "on" input controls the amplifier's output while the "off" inputs behave as open circuits.

Its low quiescent current makes it useful in isolation circuitry where power supply current is frequently limited.

MULTIPLEXER WITH DIFFERENT GAINS



CHANNEL SELECT	V_{OUT}
$> 2.0V$	$A_{V1} \times V_{IN1}$
$< 0.8V$	$A_{V2} \times V_{IN2}$

$$A_{V1} = 1 + \frac{R_3}{R_2 + R_1} \qquad A_{V2} = 1 + \frac{R_3 + R_2}{R_1}$$

PICK A VALUE FOR R_3, A_{V1}, AND A_{V2}. THEN

$$R_2 = R_3\left(\frac{1}{A_{V1} - 1} - \frac{1}{A_{V2} - 1}\right) \Big/ \left(1 + \frac{1}{A_{V2} - 1}\right)$$

$$R_1 = \frac{R_3 + R_2}{A_{V2} - 1}$$

NOTE: $A_{V2} > A_{V1}$

Each channel can have different noninverting gains.

BURR-BROWN®

Different gain for the two inputs can be created with the OPA201 by tapping different divider ratios on a common feedback network. Separate feedback networks could be used, however, the approach shown here minimizes the load which the op amp output must drive, thus maintaining the OPA201's very low (500 uA max) quiescent current.

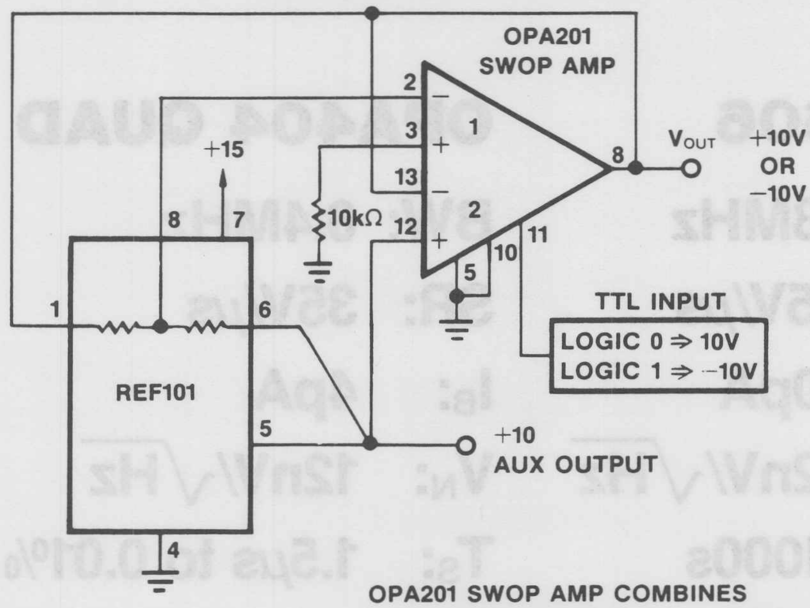
This circuit could be used to monitor two different signals with very different amplitudes, or the same input signal could be automatically switched to an appropriate gain depending on its voltage (autoranging).

The bias current cancellation resistors should be made different since the effective feedback impedance changes when the channel is switched:

R4 = (R1 + R2) // R3

R5 = R1 // (R2 + R3)

±10V LOGIC CONTROLLED



OPA201 SWOP AMP COMBINES AMPLIFIER & SWITCHING FUNCTIONS.

BURR-BROWN®

The OPA201 can be used in conjunction with the REF101 precision voltage reference to create a switchable output voltage.

This circuit makes use of the precision resistors matched resistor pair in the REF101 with the switchable inputs of the OPA201 SWOP AMP to provide a logic selectable +10 or -10 volt output. The REF101's internal resistor pair accurately inverts the output for -10 volts. The 10k ohm resistor connected to pin 3 is used for bias current cancellation, and does not need to be a precision type.

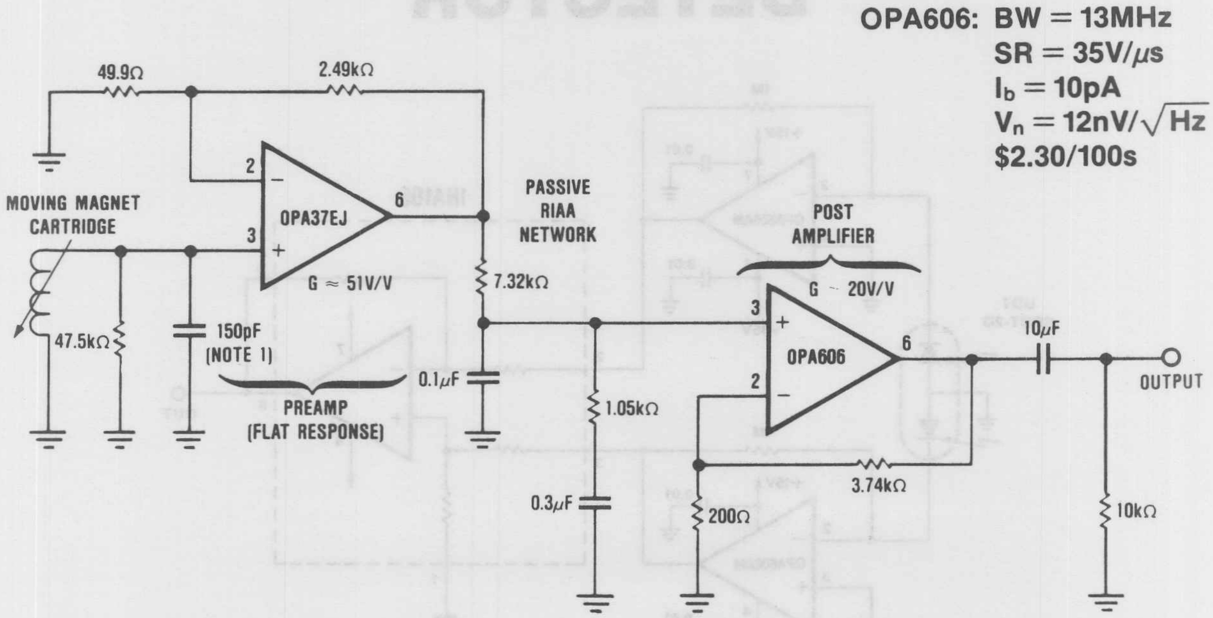
HIGH SPEED *Difet*® OP AMPS

OPA606		OPA404 QUAD *Difet*®	
BW:	13MHz	BW:	6.4MHz
SR:	35V/μs	SR:	35V/μs
I_B:	10pA	I_B:	4pA
V_N:	$12nV/\sqrt{Hz}$	V_N:	$12nV/\sqrt{Hz}$
$2.30/1000s		T_S:	1.5μs to 0.01%

The OPA606 high speed op amp has proven extremely useful in circuits where industry standard "356" type op amps have proven marginal. Broadband noise performance of the OPA606 is often an order of magnitude or more lower than other "356" type parts. Comparison of data sheets may not tell the whole story.

The OPA404 is a new quad fet amplifier. Laser trimming has brought performance unattainable with other quad op amps. Its broad range of superior performance includes offset and offset drift, noise performance, and AC behavior. At 1.5 us to 0.01%, the settling time of the OPA404 stands apart from all but a very few single op amps.

RIAA PREAMPLIFIER



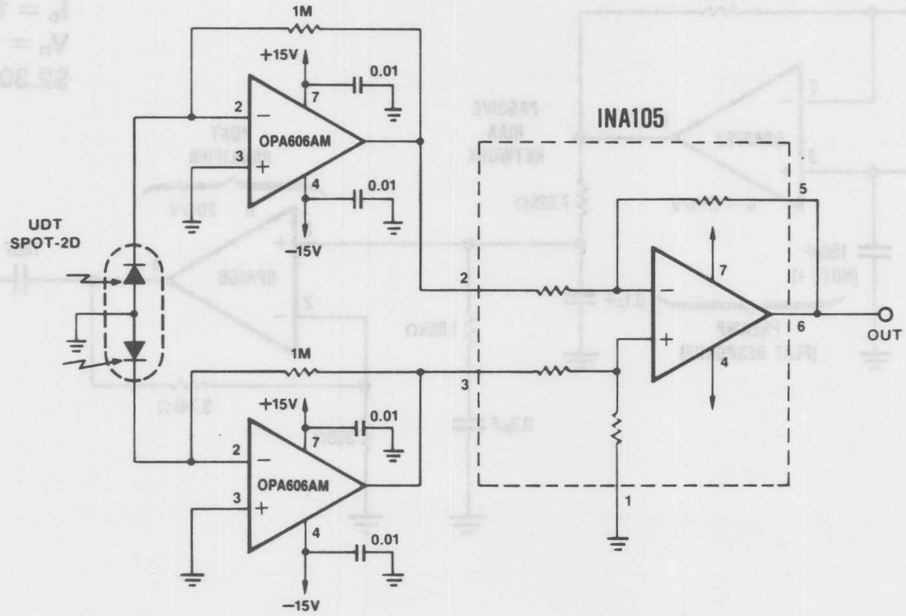
BURR-BROWN®

This phono preamplifier differs from the majority of circuits in its use of a passive equalization network. Said by many audiophiles to provide the ultimate in sonic performance, this approach requires different characteristics in the two op amps used.

The first op amp is operated as a flat gain stage. It must provide adequate signal level to drive the lossy passive equalization network without degradation in noise performance. The OPA37 is chosen because of its very low voltage noise since the source impedance--the cartridge--is low in the critical midband region (300mH at 1kHz = 2kohm). The source impedance should not be confused with the 47kohm cartridge load impedance. The amplifier's source impedance is much lower.

Following the passive equalization network, the OPA606 is chosen due to the higher voltage swings required. This device has been shown to provide improved distortion performance in noninverting circuits where the common mode voltage swing is relatively large or fast. Its output drive capability is appropriate for driving the "tape out" function and subsequent volume and tone control circuitry.

OPTICAL NULL POSITION DETECTOR



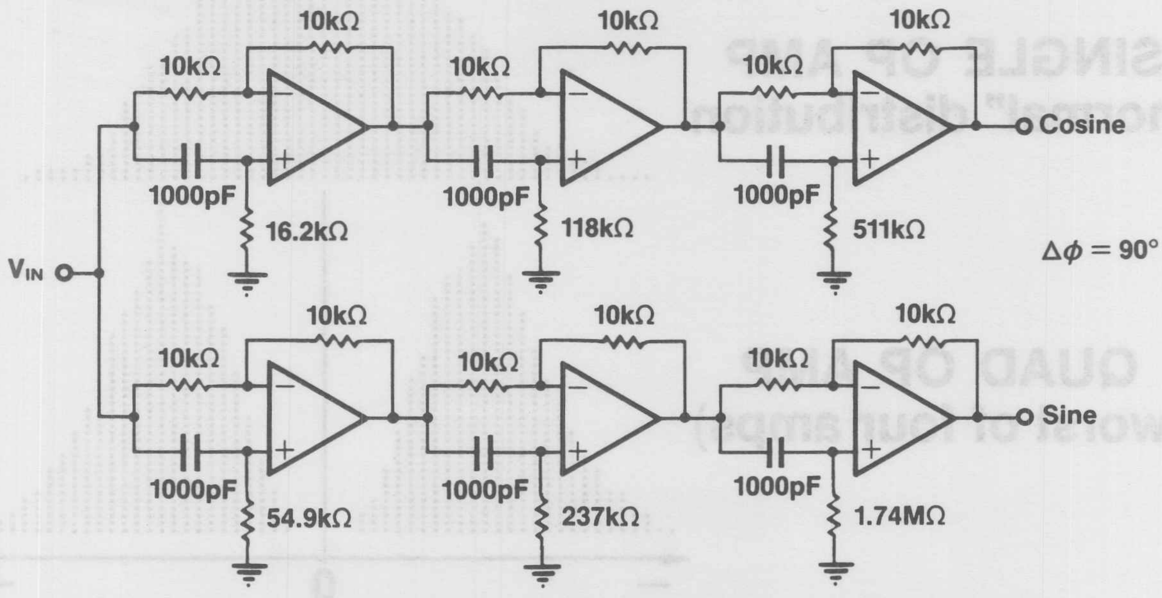
BURR-BROWN®

This application combines two optical detectors with transimpedance amplifiers connected to form a position detector. When combined with an integrated difference amplifier (described later) a single output is achieved which represents the position of an item blocking a light source.

The OPA606 allows high speed operation in this circuit. The Difet construction of the OPA606 provides many performance advantages over industry standard "156" family parts. Significant improvements will be seen in many areas including input bias current and voltage noise.

Comparisons of noise specification may be confusing. The "typical" figures published for competitive parts make the Burr-Brown OPA156 appear inferior. Burr-Brown strives to publish realistic "typical" data. COMPARE THE ACTUAL PERFORMANCE... we are very confident of the result.

90° PHASE SHIFT NETWORK WITH OPA404 QUAD



300 — 3kHz ± 0.1°

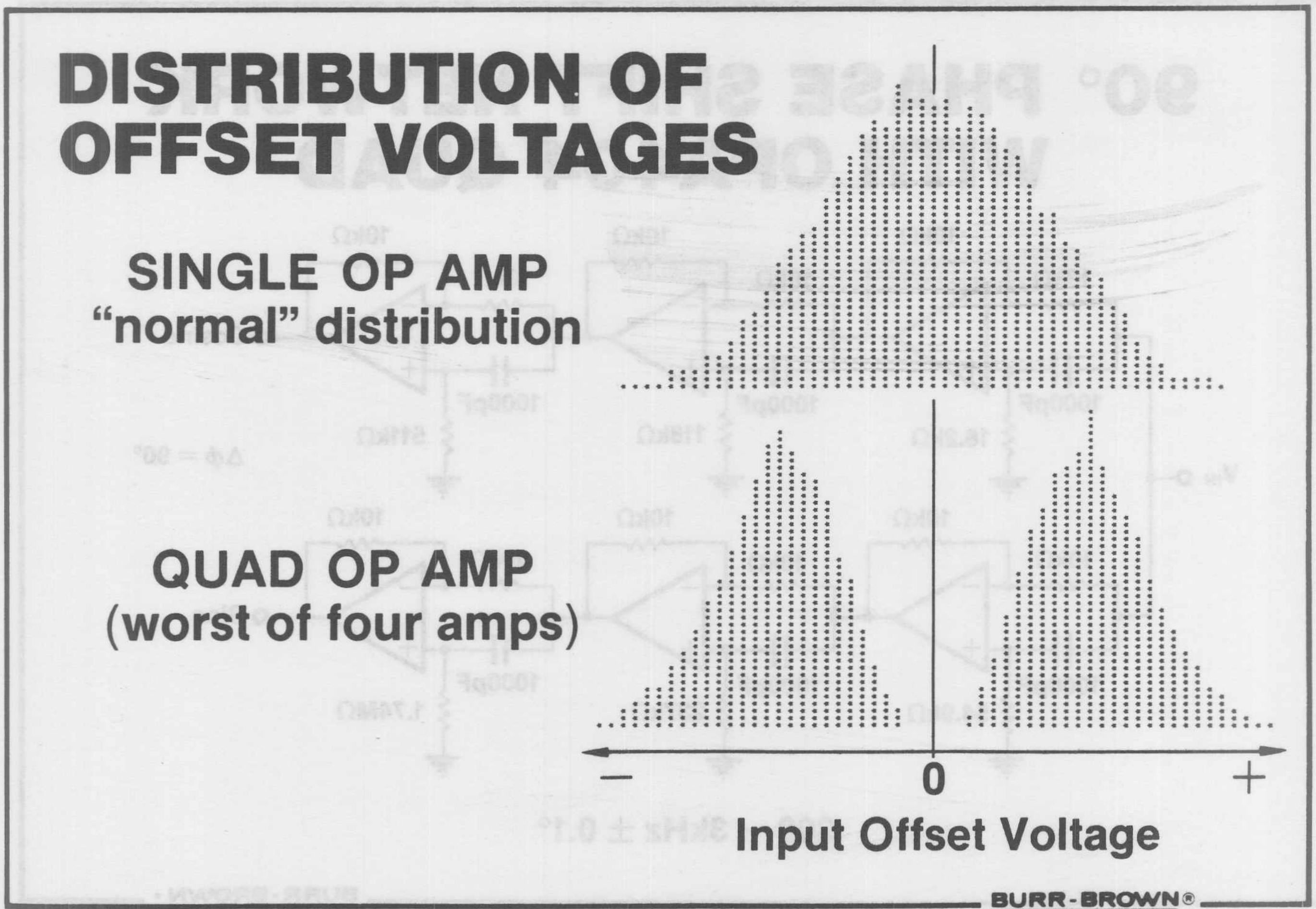
BURR-BROWN

-33-

Phase shift networks are used in communications systems for single-sideband generation. This circuit has two parallel paths, each with three all-pass networks to create phase shift while maintaining flat amplitude response. The phase shift between the two signal paths is a nearly constant 90 degrees over the required 300 to 3000 Hz communications bandwidth.

The OPA404 is an ideal op amp for this application, offering the space savings and efficiency of a quad. Impedance levels are such that a fet input op amp is needed to avoid a build-up of DC offset due to input bias current.

To avoid output frequency components which are not properly phase-shifted, the input signal should be band-limited. This is done with an appropriate filter ahead of the input.

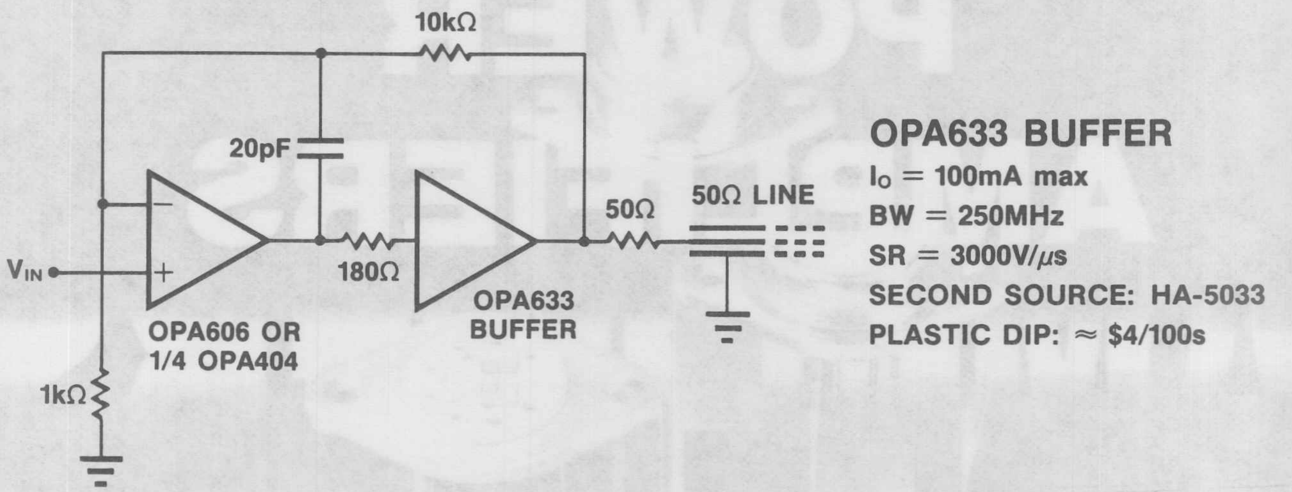


A large production lot of single op amps has a "normal" or Gaussian distribution of offset voltages. When the same distribution is applied to a quad op amp, the problem of obtaining low offset voltage grows acute.

The specification of a quad op amp must apply to the worst of the four internal op amps. With four "chances" to find an amp with poor offset, the resulting new distribution has a "hole in the middle." The specification for a quad op amp must then be set much wider. Furthermore is difficult to select for very low offset voltage since very few such units exist.

Laser trimming comes to the rescue: By laser trimming the offset voltage of each op amp on the chip, the initial distribution can be greatly tightened. The final quad distribution may still have the gap in the center, but the offset voltage specification can be set much lower.

HIGH OUTPUT CURRENT BUFFER



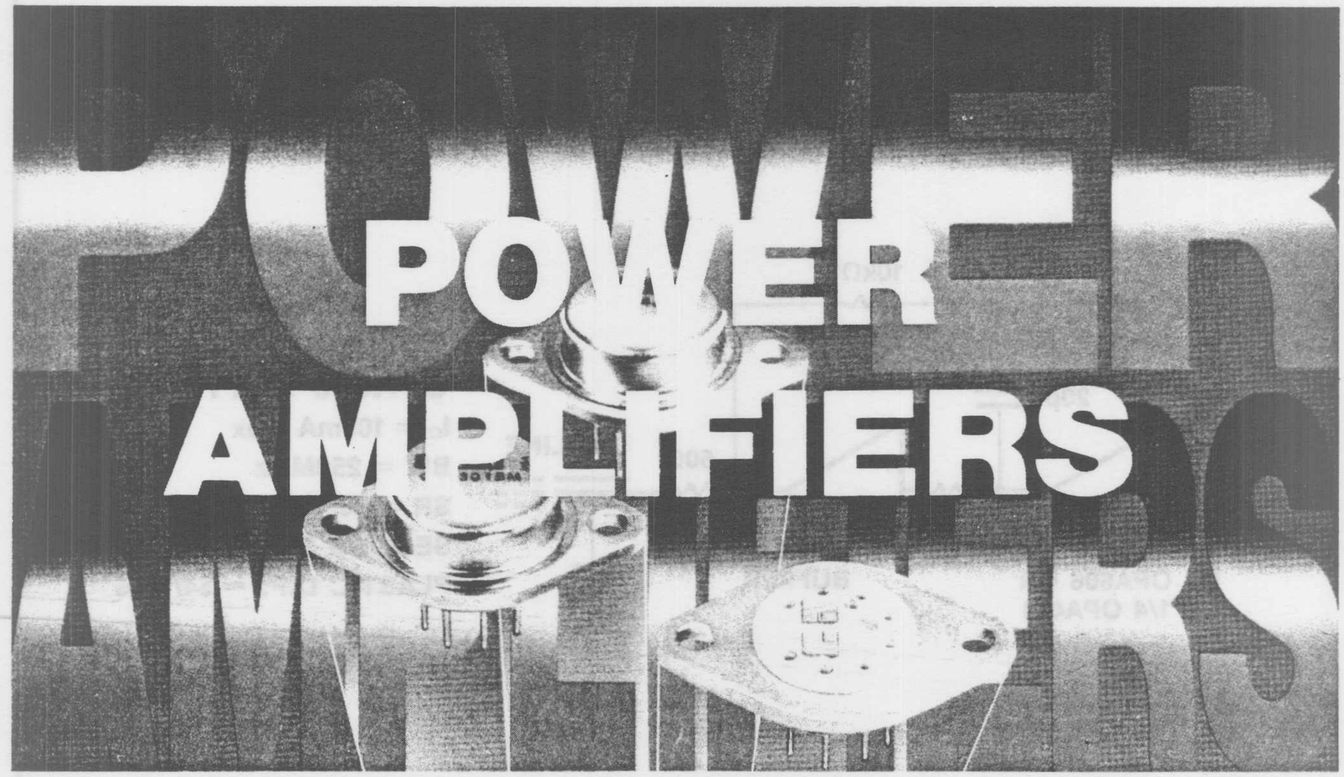
BURR-BROWN®
BB

High speed and wide bandwidth applications often require higher output current than can be accomplished with conventional signal op amps. Applications often include driving cables or capacitive loads. The OPA633 wide bandwidth buffer can solve this problem.

This device is a unity gain buffer with wide bandwidth (275 MHz) and low phase shift (10' @ 70 MHz). Its output current capability is 100 mA. It can be put inside the feedback path of most op amps. Thus the accuracy of the complete circuit is dominated by the op amp. (The errors of the buffer are divided by the loop gain of the op amp.) The composite amplifier is now capable of driving long lines and high capacitance while maintaining precision performance.

OPA633 is a second source to the HA-5033. The plastic version sells for as low as $4.00 in 100s.

note: Also consider op amps such as the OPA605 and OPA600 for high speed applications requiring moderate output currents. See BB Power Amplifiers for higher output voltage and current.



BURR-BROWN®

-36-

Just as signal op amps displaced discrete design in the 1970's, the availability of op amps capable of high current and voltage operation are having their impact in the 80's. Designers are finding that months of effort can be saved by using power op amps to replace difficult and tricky discrete designs.

Power op amps have found use in a wide variety of motor, speaker, actuator, and deflection drive applications. Programmable voltage and current sources for ATE and pin driver applications are also common applications.

OPA512
SIMPLIFIED SCHEMATIC

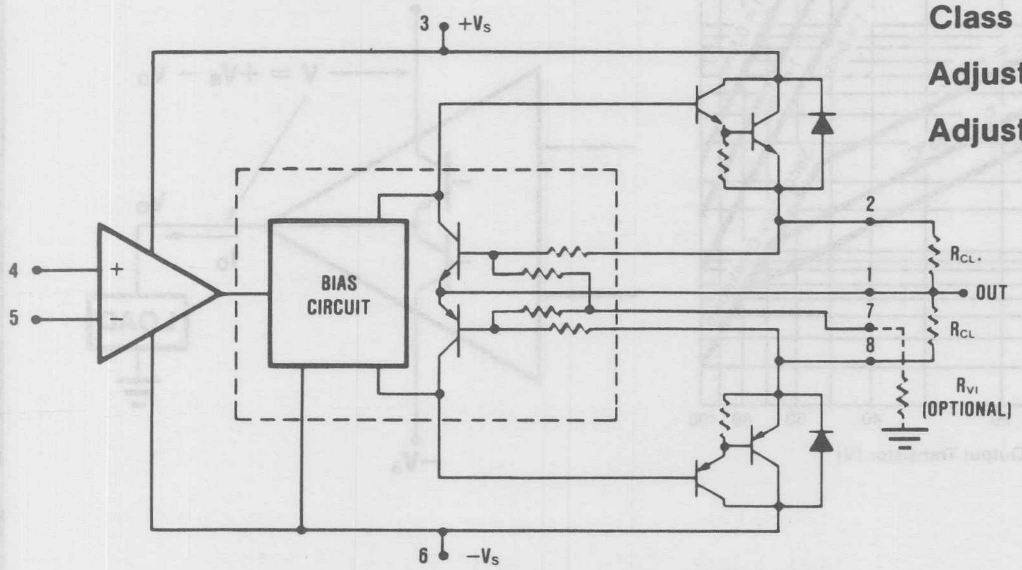
$V_S = \pm 10$ to $\pm 50V$

I_{OUT} up to 15A

Class A/B Output Stage

Adjustable Current Limit

Adjustable V-I Limit



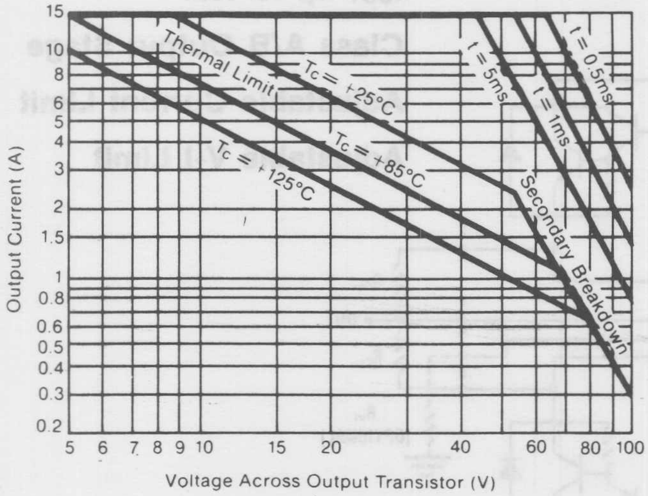
BURR-BROWN®

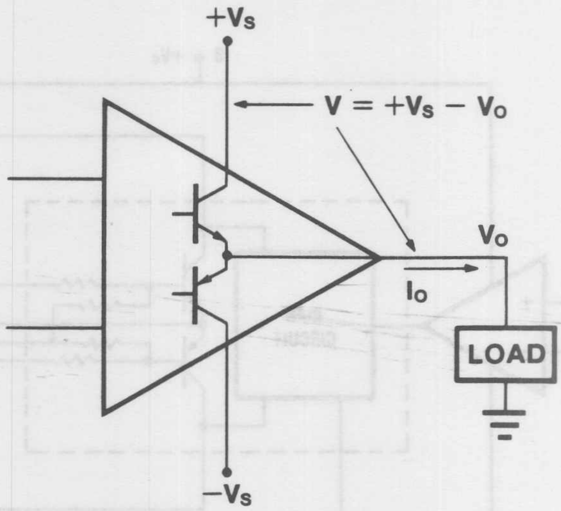
-37-

The OPA512 power amp is representative of a number of products covering a variety of voltage and current ranges. A conventional op amp type input is combined with a high voltage/current output stage. Many models have a programmable current limit like the OPA512. Other amplifiers available include:

	MODEL	+-Vs	Iout	Comments
High Current:				
	OPA512	50	15 A	Class A/B, Hi current
	OPA511	30	5 A	Class A/B, gen purpose
	OPA501	40	10 A	High Output current
	3573	34	2 A	General purpose
	3571	40	1 A	FET input
	3572	40	2 A	FET input
High Voltage:				
	3584	150	15 mA	High Speed, FET
	3583	150	75 mA	FET input, Hi current
	3582	150	15 mA	" "
	3581	75	30 mA	" "
	3580	35	60 mA	" "

OPA512
SAFE OPERATING AREA





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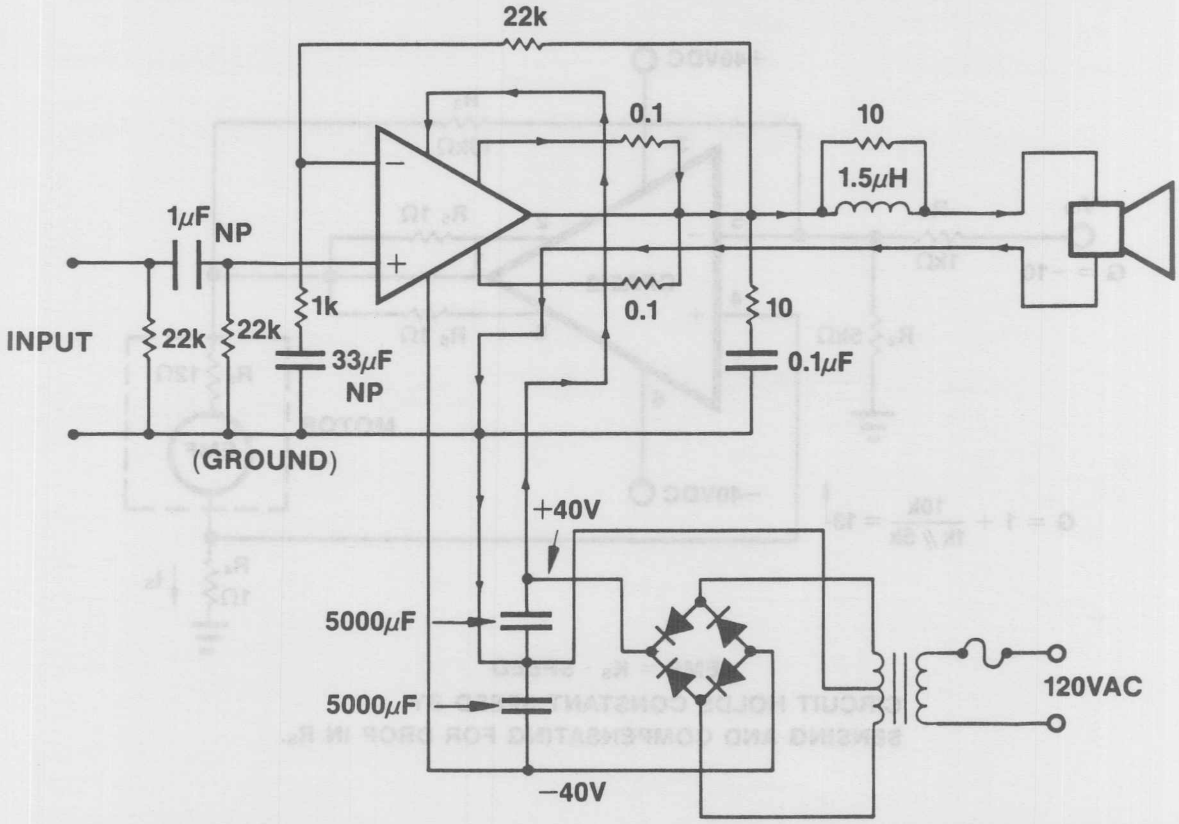
Safe operating area (SOA) is a measure of the allowable combination of output current through, and voltage across the power transistors, and is a key specification of a power amplifier. The OPA512 fully specifies SOA at 25'C and 125'C, relieving the designer of the pitfalls of loosely specified transistor parameters.

Evaluation of the SOA required in a given application is one of the most important aspects of power and high voltage amplifier application design. Consideration of the nature of the load including reactive and reverse EMF behavior may influence the product selection and application circuit.

Burr-Brown applications note AN-123.

AUDIO POWER AMP—OPA512

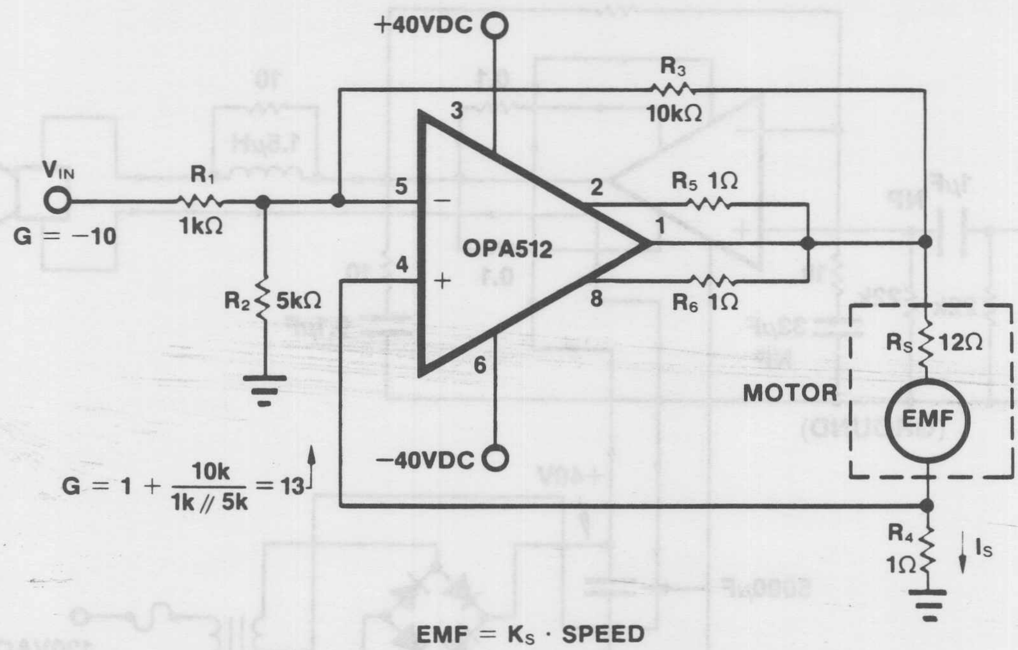


The OPA512 can function as a high power audio power amplifier and this application illustrates several principles useful in other power amp circuitry. The input is AC coupled to prevent and DC or excessively low frequency from being passed to the speaker. Gain is set at 23 which allows full output to be achieved with approximately 1V rms input.

An unregulated power supply is used to provide approximately +-40 volts under no-load conditions. This voltage allows a margin of safety for high power line voltage. The maximum power supply voltage specified for the OPA512 is +-50 volts (SM grade).

One of the considerations in critical power amplifier applications is the physical layout of high current paths. Ideally, each high current path should be closely paired with the opposing return current path. This is illustrated with arrows for positive half-cycles. This lowers inductance in the current path and minimizes the radiation of currents into low level input circuitry.

DC MOTOR SPEED CONTROL



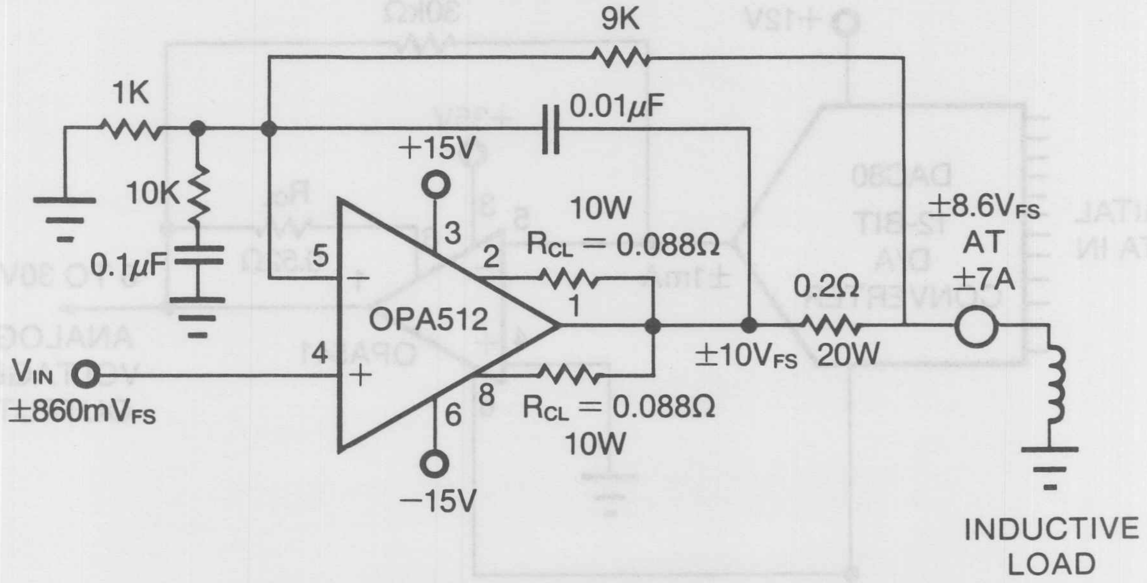
CIRCUIT HOLDS CONSTANT SPEED BY SENSING AND COMPENSATING FOR DROP IN R_S.

BURR-BROWN®

Demonstrating the functional value of a precision op amp input, this DC motor speed controller compensates for the voltage dropped in the motor series resistor and current sense resistor. By compensating for this drop, the motor EMF is forced to be directly proportional to the input voltage. Since the motor's EMF is proportional to its rotational speed, accurate control of the speed is established.

The gain of the positive feedback path is controlled by R2 which sets the desired gain of 13. R2 does not affect the primary inverting signal path gain at Vin. Small variations in motor series impedance can be accommodated by making R2 adjustable.

Protection For Power Amplifiers



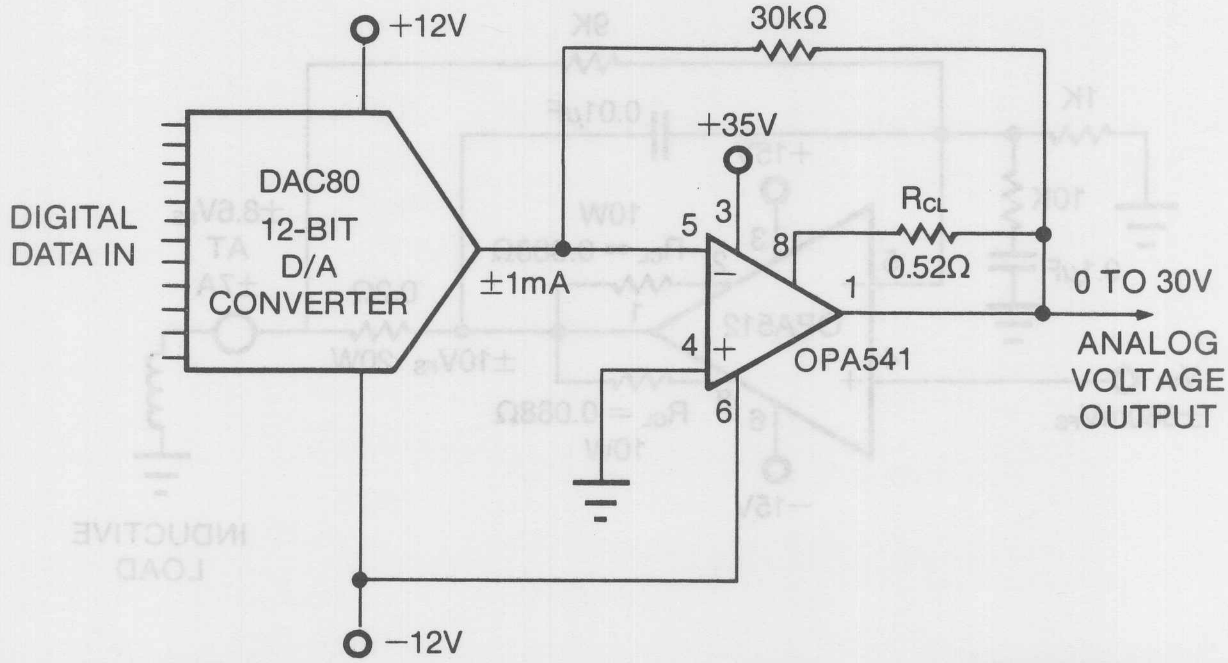
BURR-BROWN®

-40A-

The Safe Operating Area (SOA) of a power amplifier is often the single most important consideration in achieving a reliable design. This relates to the power in the output transistors (Vce x Ic) and not the power in the load. Four ways to protect the amplifier are shown. First, limit the output current with limiting resistors. Second, to preserve stability, limit the bandwidth with a feedback capacitor. Third, for stability, increase the dynamic gain with an RC on the inverting input to ground. Fourth, add a small resistor in series with the output.

In the circuit shown, the voltage on the left side of the output resistor is higher than the right side. The load voltage holds constant with increasing load current, although the amplifier output voltage increases. The advantage of the output resistor is protection from transients. As a load current spike rises, the voltage across the resistor inside the loop rises, thus buffering the amplifier output from the load.

Computer Programmable Power Supply

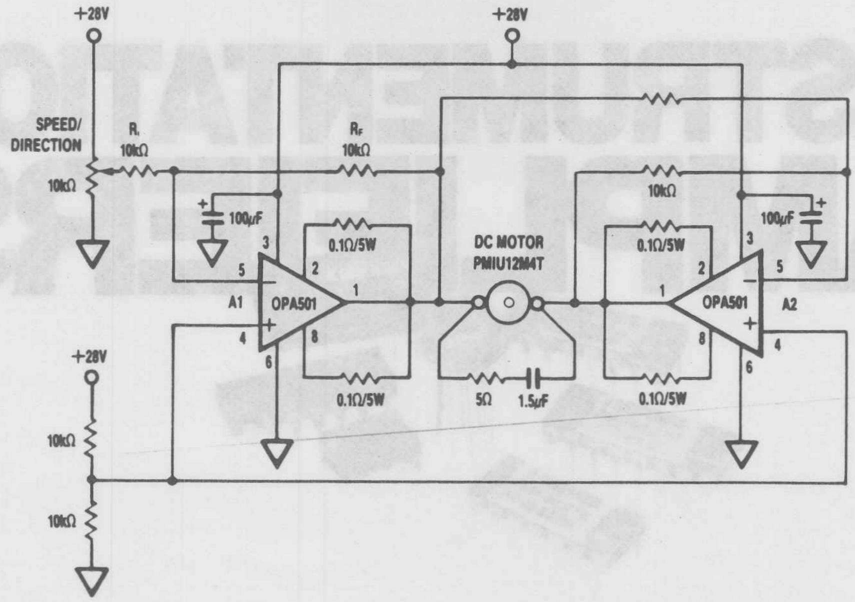


BURR-BROWN®

-40B-

For test or calibration purposes, it is often desirable to apply precision voltages to a power circuit. One technique that uses very few components is the digital-to-analog converter driving a power amplifier. The +40V and -12V power supplies connected to the amplifier allows the output voltage to range from 0V to +35V for input digital codes of all ones or all zeros. This circuit can also be used to generate power waveforms, such as sinewaves, triangular waves, or specially shaped control signals.

SINGLE SUPPLY— MOTOR CONTROL CIRCUIT



BURR-BROWN®

-41-

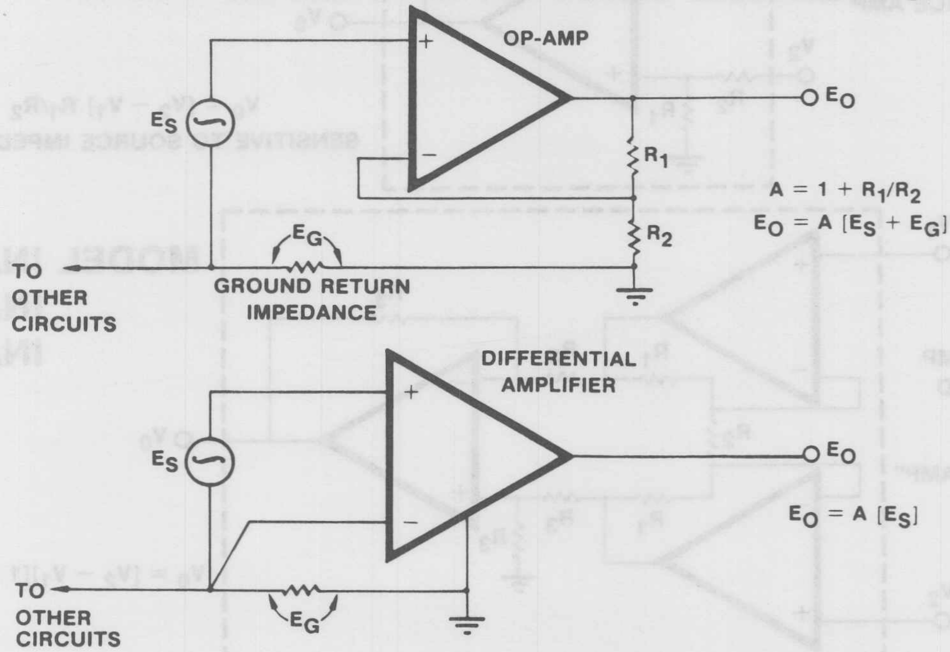
Bridge output configurations are often used with power and high voltage amps to extend the output voltage swing attainable from a single supply voltage. By using complementary (inverted) drive signals, bipolar voltages can be delivered to the load which approach twice the supply voltage in peak-to-peak swing capability. Thus, direction of a DC motor can be reversed with single supply operation.

Maximum slew rate at the load is twice that attainable with a single power amplifier. This technique also improves safe operating area since the voltage drop and dissipation is shared equally between the two power amps.

Improvements in monolithic technology have brought lower prices, and performance unattainable with discrete circuitry. This has brought instrumentation amplifiers acceptance as a common electronic component.

See the Instrumentation Amplifier brochure for a brief summary of Burr-Brown products.

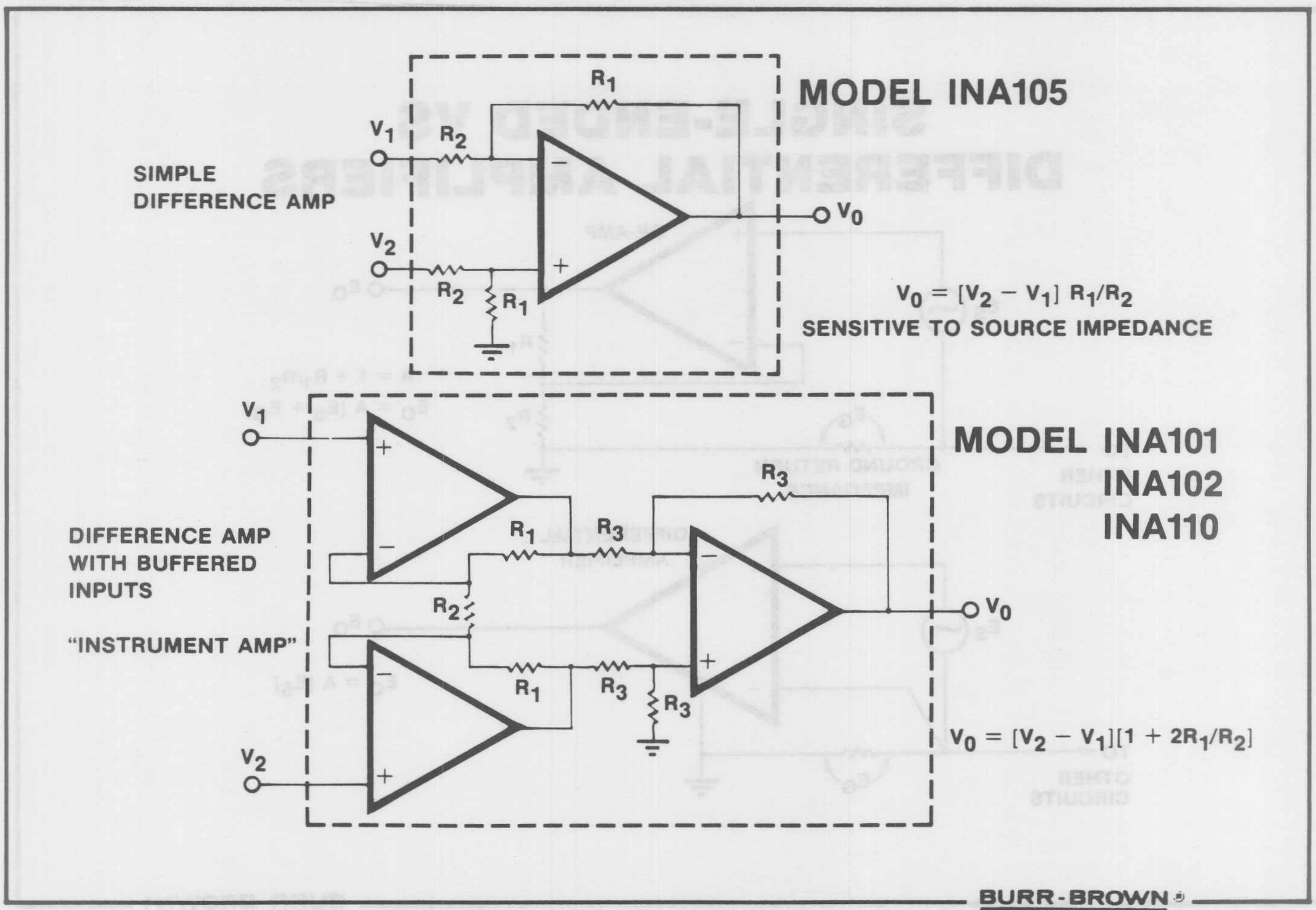
SINGLE-ENDED VS DIFFERENTIAL AMPLIFIERS



BURR-BROWN®

Single-ended amplifiers with high input impedance make input amplifiers which are useful in many situations but they can suffer from errors due to ground drops. Currents flowing in circuit board traces or system ground wiring can easily create voltage drops which are summed with the desired input signal and amplified at the output.

The differential input amplifier can reject these error voltages by sensing directly across the source voltage, thus rejecting any ground drop voltages as a common-mode signal.



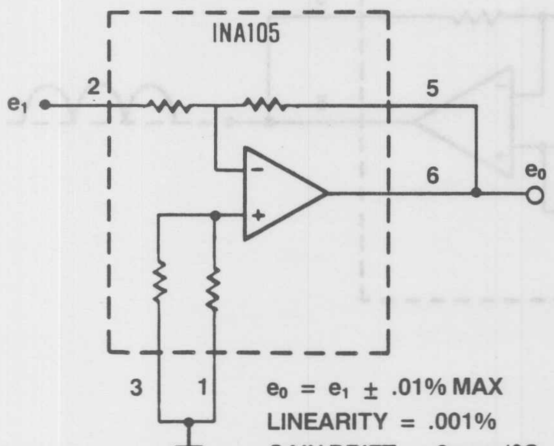
BURR-BROWN®

A simple difference amp (model INA105), comprised of an op amp and four precision trimmed resistors, is useful in a wide variety of applications. It can be employed with excellent results where the source impedance is low or well-defined. Its sensitivity to source impedance, however, can cause unacceptable gain and common-mode rejection (CMR) errors in other applications.

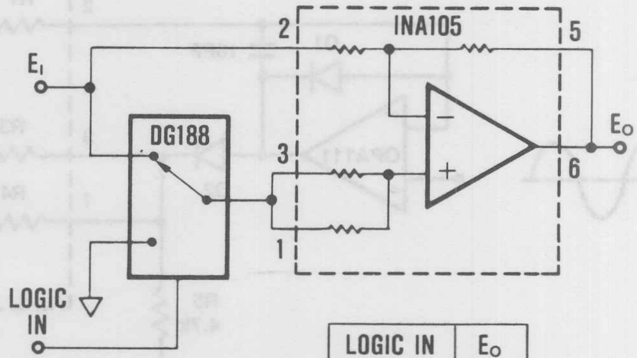
The buffered "instrumentation amplifier" (such as the INA101, INA102 and INA110) combines high impedance buffers with the difference amp. The gain of the input buffers is controlled by R1 and R2, while the rejection of common-mode signals (CMR) depends on the ratio of the resistors in the output difference amp stage.

THE VERSATILE DIFFERENCE AMP

PRECISION INVERTER



$e_0 = e_1 \pm .01\%$ MAX
LINEARITY = .001%
GAIN DRIFT = 2 ppm/°C



LOGIC IN	E_O
0	$-E_1$
1	$+E_1$

BURR-BROWN®

The simple difference amplifier is too often viewed as special purpose component with limited usefulness. But its simplicity brings it versatility.

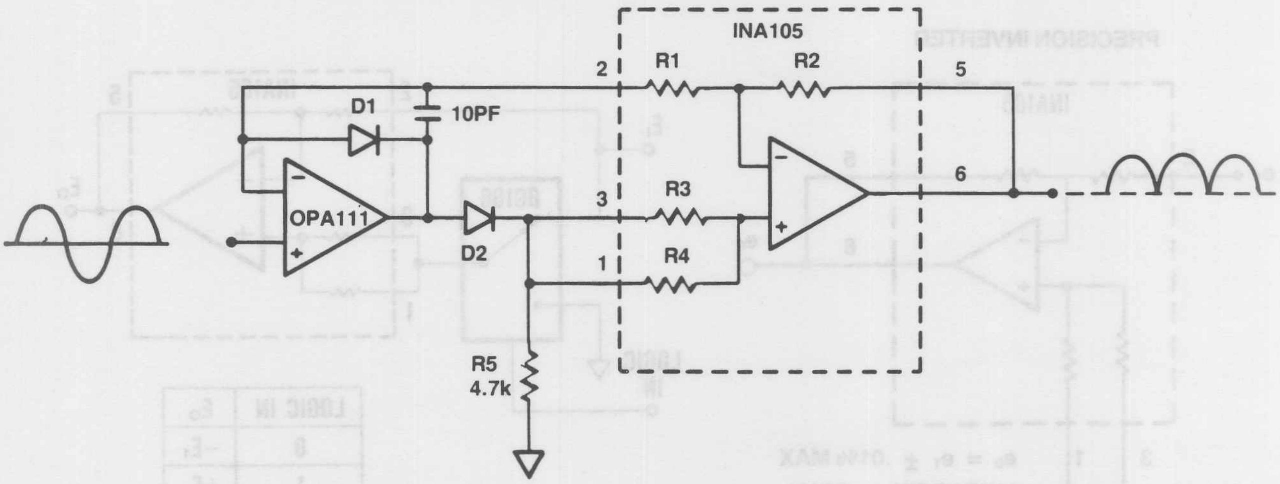
When a precision inverter is required in a system, the INA105 easily performs the function. Its precision trimmed temperature tracking resistors provide excellent gain accuracy and drift... performance difficult to achieve with an op amp and user provided resistors. By paralleling pin 1 and pin 3, the effects of bias currents are canceled. (An op amp without bias current cancellation is used.)

The addition of a CMOS switch to the basic inverter circuit provides a switchable gain of +1 or -1 under logic control. When pins 1 and 3 are switched to ground, it functions as a precision inverter like the circuit on the left. When switched to the input, the gain of -1 is countered by a gain of +2 at the non-inverting input. Therefore, the net gain is +1. Note that in both switch positions, any resistance in the switch is in series with a high impedance input and therefore has virtually no affect on gain accuracy.

"Monolithic difference amp eases the design of a variety of circuits," EDN, March 20, 1986.

Note: Also consider the OPA201 SWOP AMP for gain and polarity switching circuits.

ABSOLUTE VALUE CIRCUIT



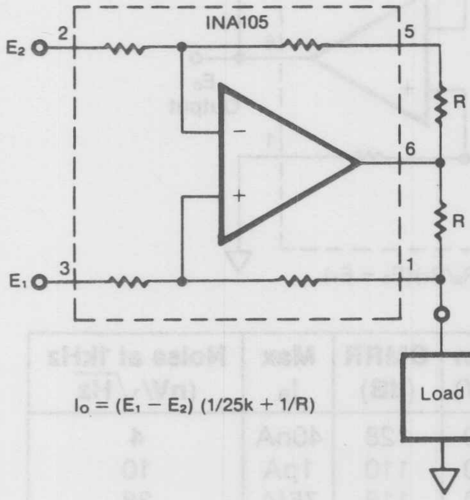
The versatility of the INA105 difference amp is demonstrated in this full-wave rectifier circuit. The difference amp provides the required precision components (matched resistors) to provide equal gain on positive and negative half cycles.

Negative inputs are buffered by A1 and applied to pin 2 of the difference amp--the inverting input. (D2 is "off" and pin 3 is held a ground by R5.)

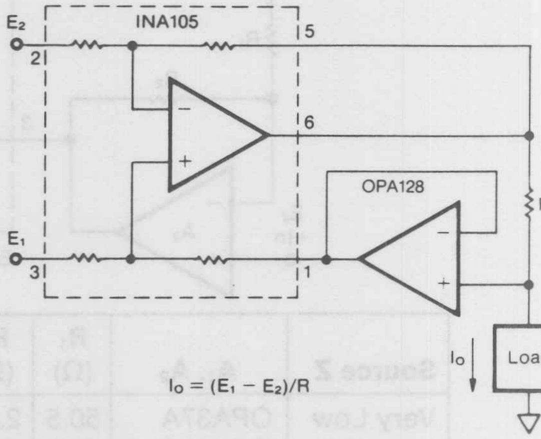
Positive inputs are applied equally to inverting and noninverting inputs of the difference amp. By connecting pins 1 & 3 together, however, the noninverting gain is +2, thus providing a net gain of +1 at the output.

VOLTAGE-TO-CURRENT CONVERTERS

MODERATE CURRENTS



ULTRA-LOW CURRENTS



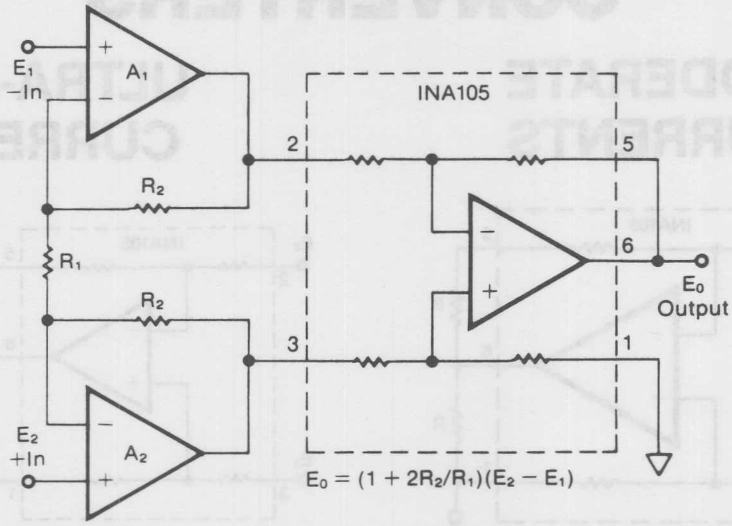
BURR-BROWN

The Howland current source (or current pump) is easily implemented using the INA105 difference amplifier. It accurately sources a current proportional to the difference of two input voltages.

A clever variation of the Howland current source allows operation at very low output current. By using a fet input op amp such as the OPA128 (75 fA input bias current), an extremely high resistor value, R, can be used without introducing significant errors. The additional op amp also simplifies the transfer equation by eliminating loading of the sense resistor by the feedback resistors. It also eliminates the INA105's internal 25 kohm resistors' values from the transfer equation. These resistors are fabricated and laser trimmed for an accurate matching, but not for absolute resistance value.

note: Also consider the XTR110 for voltage-to-current conversion applications.

INSTRUMENTATION AMPLIFIER



$$E_0 = (1 + 2R_2/R_1)(E_2 - E_1)$$

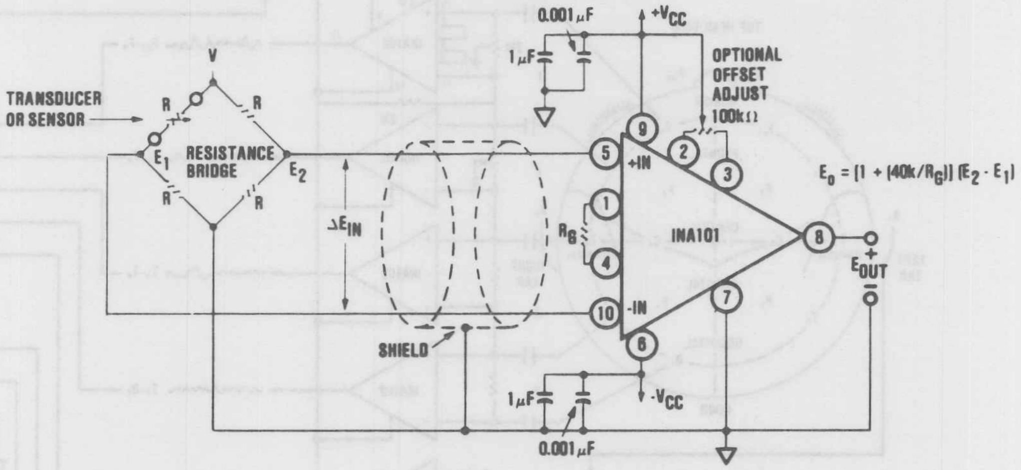
Source Z	A_1, A_2	R_1 (Ω)	R_2 (Ω)	Gain (V/V)	CMRR (dB)	Max I_B	Noise at 1kHz (nV/$\sqrt{Hz}$)
Very Low	OPA37A	50.5	2.5k	100	128	40nA	4
Very High	OPA111B	202	10k	100	110	1pA	10
Ultra High	OPA128LM	202	10k	100	118	75fA	38

BURR-BROWN®

The INA105 differential amplifier can be combined with high performance op amps to achieve special input properties. For very low or very high source impedance, this approach provides improved performance over integrated instrumentation amplifiers. The OPA27's very low input voltage noise, offset voltage and drift achieves high accuracy with very low source impedance. The very low input bias current of the OPA128 provides exceptional performance with extremely high source impedance.

Precision laser trimming of the INA105 provides the critical common-mode rejection performance which is difficult to achieve with discrete components. The input stage resistors, Rg and Rf, only affect the gain.

BRIDGE SENSOR AMPLIFICATION



Amplification of a Differential Voltage from a Resistance Bridge.

INA101:

- ULTRA-LOW VOLTAGE DRIFT: 0.25μV/°C
- LOW OFFSET VOLTAGE: 25μV
- LOW NONLINEARITY: 0.002%
- LOW NOISE: 13nV/√Hz at f_O = 1kHz
- HIGH CMR: 106dB at 60Hz
- HIGH INPUT IMPEDANCE: $10^{10}\Omega$
- LOW COST

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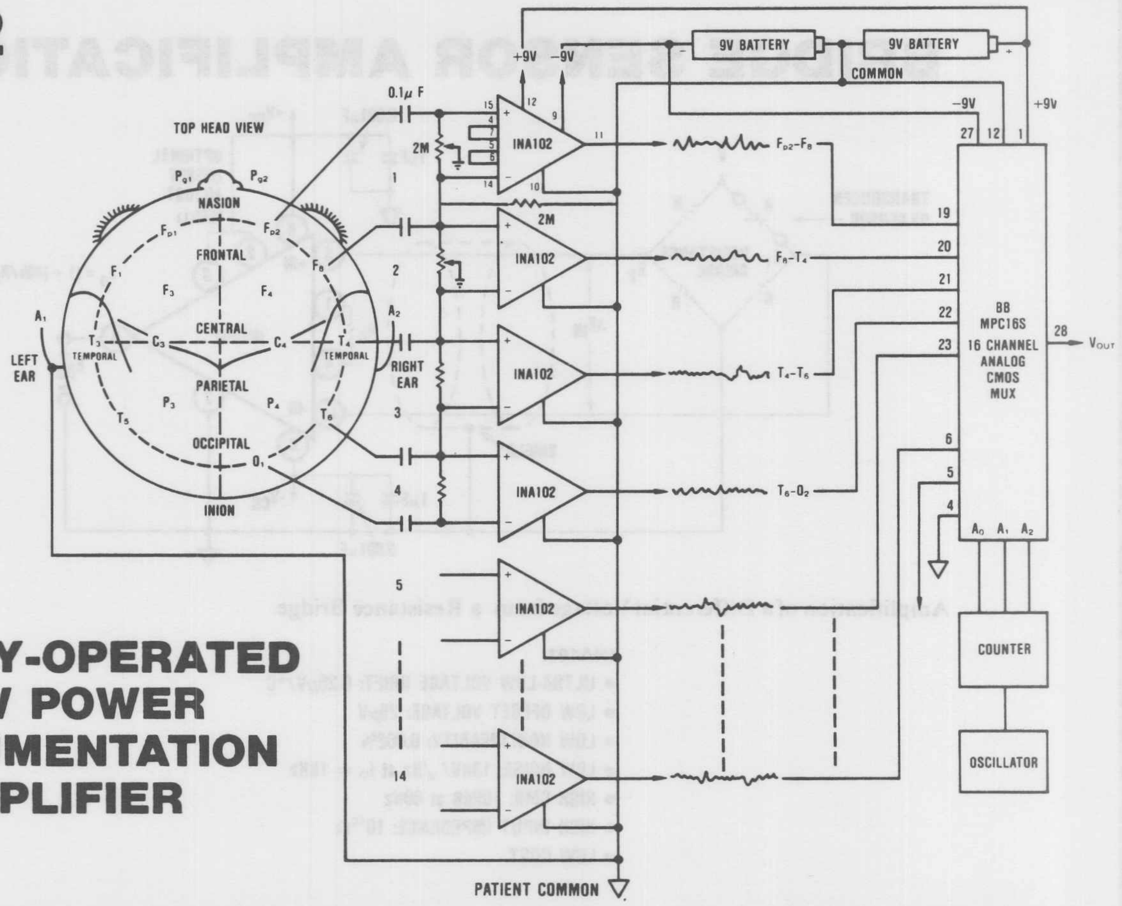
The small differential output voltage of a bridge sensor is superimposed on a large common-mode voltage (usually half the excitation voltage). The instrument amp effectively rejects this common-mode voltage and amplifies the desired differential signal.

The INA101 is ideally suited to such applications--its high CMR, ultra-low offset voltage and drift maintain outstanding accuracy. Because of the very low initial input offset voltage (25uV--best grade) the optional offset adjustment can in most cases be eliminated. Should offset adjustment be required due to offsets in the bridge, the bridge itself should be trimmed. Using the offset adjust on the INA101 for this purpose can introduce excessive drift.

The INA101P is very cost-effective in a plastic package--$4.95 in 100s brings precision performance to low cost applications.

INA102



BATTERY-OPERATED LOW POWER INSTRUMENTATION AMPLIFIER

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Battery operation becomes feasible with the INA102. This complete instrumentation amplifier operates on 750uA max, offering new possibilities in low power, high accuracy applications. Many medical applications require multiple inputs and battery operation for safety and low noise. The INA102 is ideal for this application.

The INA102 has internal gain setting resistors which provide pin-strapped gains of 1, 10 and 100. Accurate internal resistor tracking yields excellent gain drift as well. In spite of the very low quiescent current of this device, it achieves remarkable precision. Key specifications include--

Offset Voltage--	100 uV max
Offset Voltage Drift--	2 uV/'C max
CMR--	90 dB max
Gain Drift--	5 PPM/'C max
Nonlinearity--	0.01 % max
Price--	8.95 (100s)

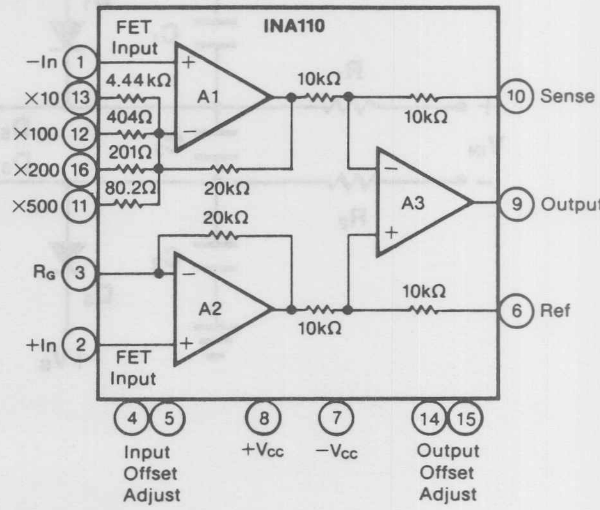
"Instrumentation amp addresses power-miser circuit applications," EDN magazine, January 23, 1986.

INA110

Fast-Settling FET-Input Very High Accuracy INSTRUMENTATION AMPLIFIER

FEATURES

- LOW BIAS CURRENT: 50pA, max
- FAST SETTLING: 4μs to 0.01%
- HIGH CMR: 106dB, min; 90dB at 10kHz
- CONVENIENT INTERNAL GAINS: 1, 10, 100, 200, 500
- VERY-LOW GAIN DRIFT: 10 to 50ppm/°C
- LOW OFFSET DRIFT: 2μV/°C
- LOW COST
- PINOUT COMPATIBLE WITH AD524 AND AD624, allowing upgrading of many existing applications



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Key features of the INA110 set it apart from previous instrumentation amplifiers:

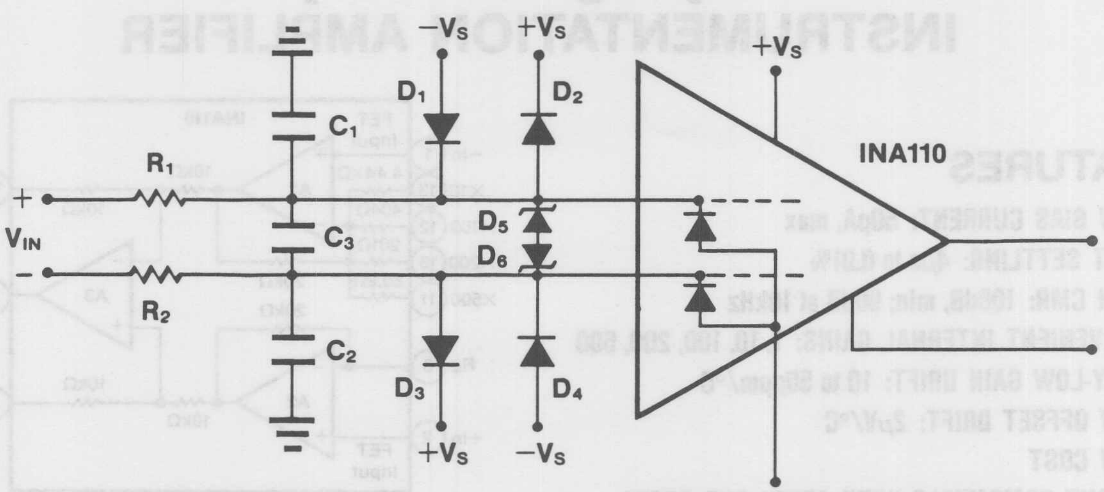
First and foremost, it is the first monolithic FET input instrumentation amplifier. Input bias current performance of 50 pA maximum makes it usable in very high impedance applications with excellent accuracy.

The INA110 is fast settling. Only 4 us is required to settle within 0.01%, making it the fastest monolithic instrumentation amplifier available. Excellent settling time is maintained over a very wide gain range.

Internal gain setting resistors allow accurate, drift-free performance. Gains of 1, 10, 100, 200 and 500 place gain steps where they are most needed. A majority of low signal level applications use gains of 100 to 500. Placing an intermediate step at G=200 allows virtually any gain to be programmed without significant degradation of gain drift.

Other gain steps are possible by paralleling combinations of the gain set pins. Gains of 300, 600, 700, and 800 can be achieved. While the accuracy of these secondary gain steps is somewhat compromised, the gain drift remains excellent. With a large number of internal gain steps available in the critical 100 to 600 range, external resistors can be added to create any needed gain, with minimal degradation of gain drift performance.

FET INPUT I.A. ALLOWS INPUT FILTERING & PROTECTION



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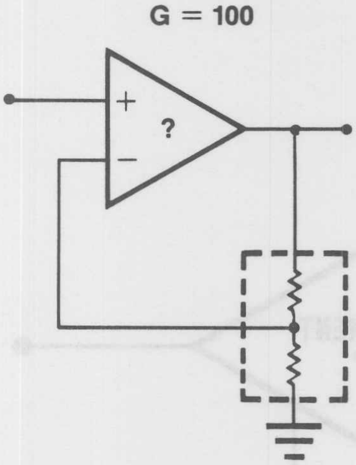
One of the most common applications requiring a FET input instrumentation amplifier arises from the need for input clamping and filtering.

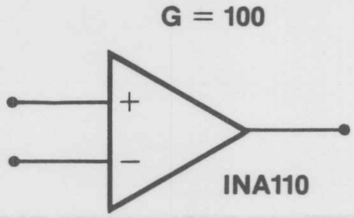
Large data acquisition systems often have signals coming from long distances through very noisy environments. When the necessary input resistors are added for filtering and clamping, input bias and offset currents create errors. To minimize these errors, resistor values must be made low and capacitor values made large. The FET input instrumentation amp avoids this trade-off.

Considerations:

1. R1*C1 matching with R2*C2 affects CMR at high frequency.
2. C3 filters differential input signals only.
3. Beware of diode leakage... especially at high temperature.
4. Diode clamps to -Vs (D1 and D4) are not required if input current in the internal diode clamps is limited to 1 mA.

G = 100 WITH OP AMP VS. G = 100 WITH INA110





SETTLING TIME	7.5μs MAX. TO 0.01%
SLEW RATE	17V/μs TYP.
V_{OS}	250μV
V_{OS}/TEMP	2.5μV/°C
FET INPUT	50pA MAX.
GAIN ACCURACY	±0.1% INTERNAL
GAIN DRIFT	±5ppm/°C INTERNAL
NOISE	10nV/Hz WIDEBAND
I_Q	4.5mA MAX.

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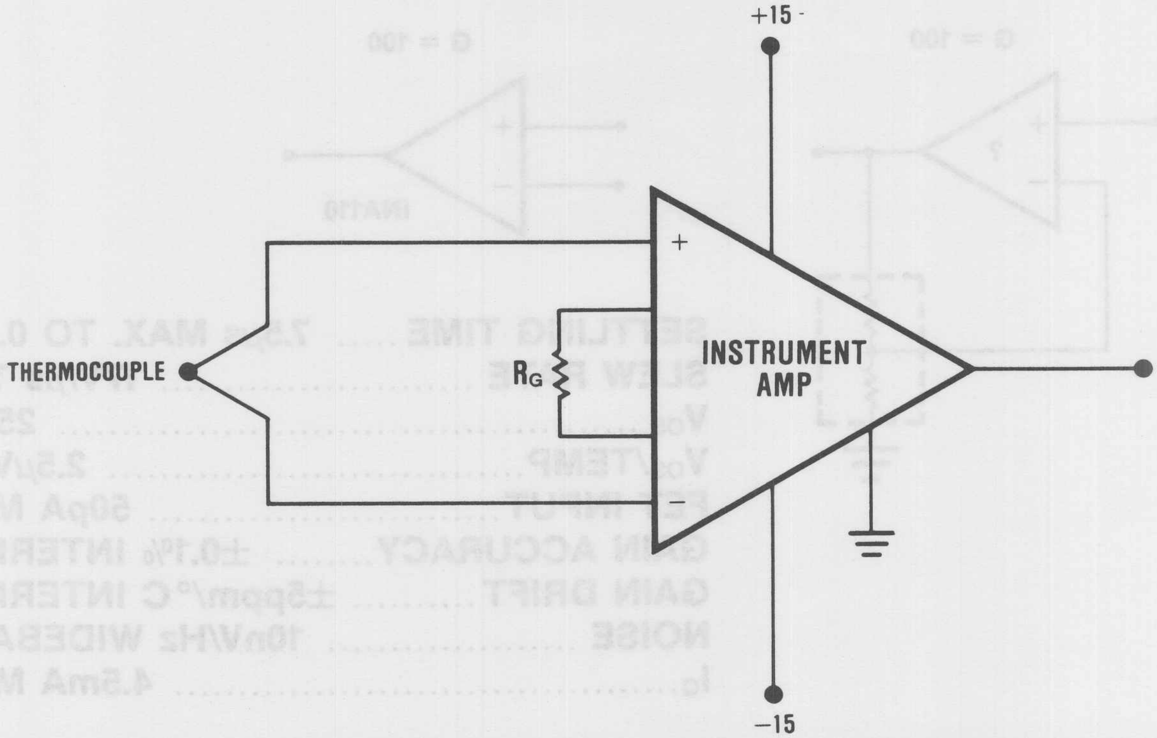
Think of the INA110 as a basic gain block. It is useful in many applications not requiring all the aspects of an instrumentation amplifier. For many applications requiring wide bandwidth at moderate to high gain, the INA110 may be the best choice.

Consider a situation requiring a gain of 100 amplifier: The INA110 provides unique overall performance. Can you select an op amp which provides equal or better performance? We couldn't. Various op amps may be equal or better in a few performance areas, but fail to measure up in overall performance.

Furthermore, the INA110,s internal gain setting resistors provide accurate, temperature-stable gain. With the op amp approach, this would require an external precision resistor network.

WILL THIS CIRCUIT WORK?



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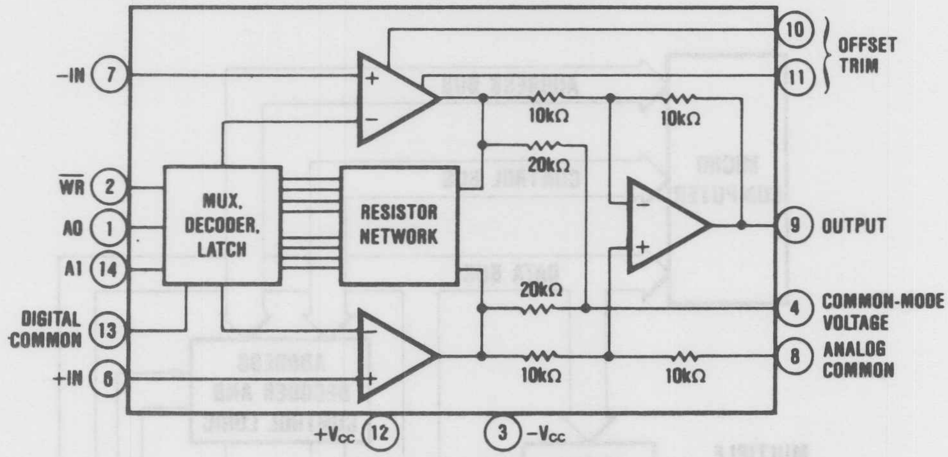
Nope, it won't.

Without a path for input bias current to flow to ground, the output of the INA101 will swing to one of the power supply rails. By adding a 100kohm resistor to ground on one of the inputs a bias current path is established and the circuit will perform as expected. If the source impedance is very high, separate resistors should be connected from each input to ground.

BLOCK DIAGRAM PGA200/201



FEATURES

- DIGITALLY-PROGRAMMABLE GAIN
  - DECADE MODEL–PGA200
    GAINS OF 1, 10, 100, 1000
  - BINARY MODEL–PGA201
    GAINS OF 1, 8, 64, 512
- EXCELLENT GAIN ACCURACY (0.02%, max)
- LOW GAIN NONLINEARITY (0.012%, max: G = 1000)
- LOW GAIN DRIFT (10ppm/°C max: G = 1000)
- 2-BIT LATCHED TTL-COMPATIBLE GAIN CONTROL
- LOW OFFSET VOLTAGE (25μV RTL MAX: G = 1000)
- LOW OFFSET VOLTAGE DRIFT (0.30μV/°C max: G = 1000)

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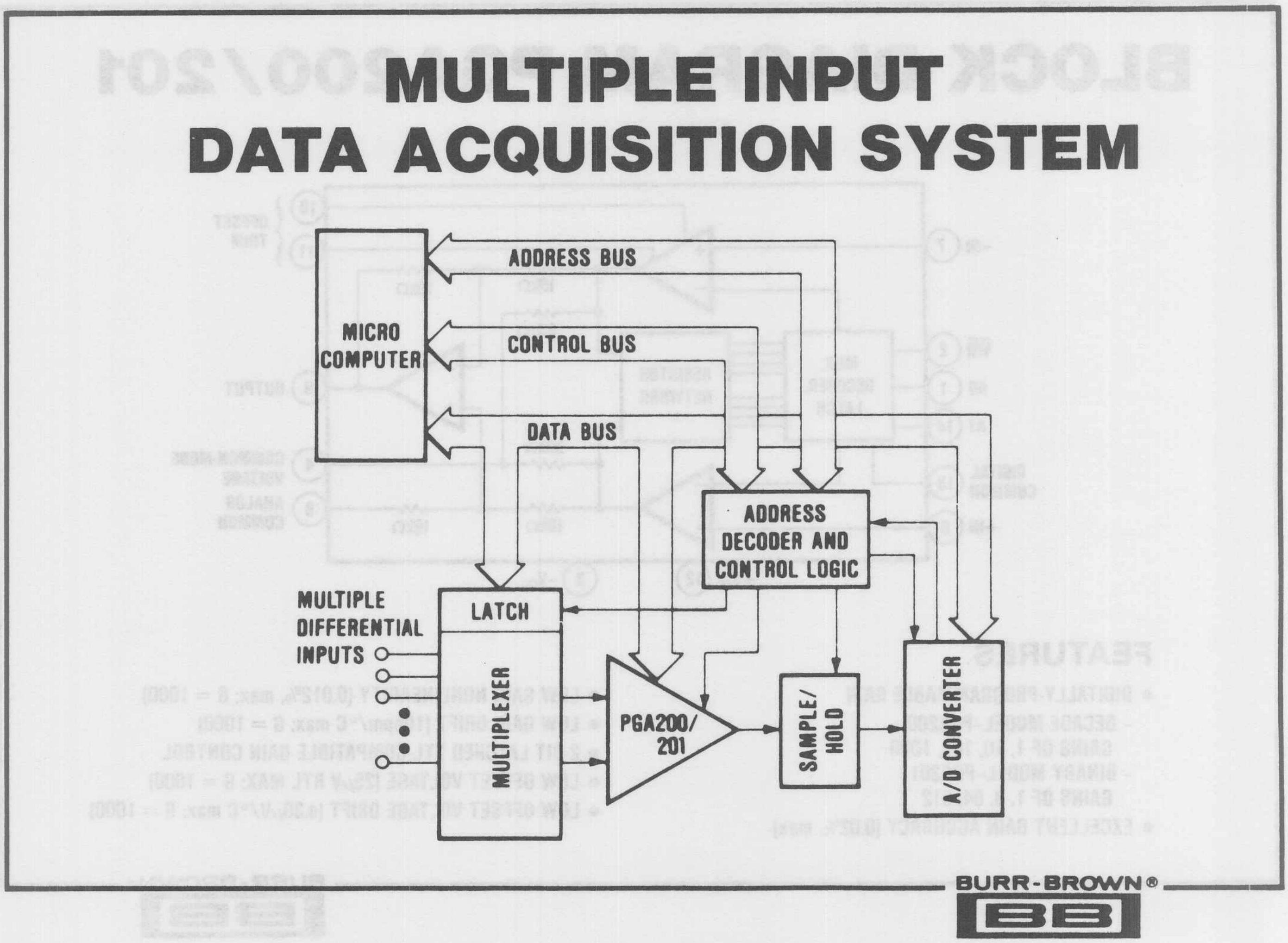
The PGA200 is an instrument amp with digitally selectable gain. A multiplexer/decoder/latch is combined with a three op amp type instrument (similar to the INA101) to select one of four possible gains:

PGA200: GAIN = 1,10,100,1000 (decade)
PGA201: GAIN = 1,8,64,512 (binary)

max gain error: +/- 0.02%

Consider using the binary gain step version in data acquisition applications where the inputs are converted to digital and processed in a computer. Results can be scaled and and compared to decision point values using shifts and binary math (fast!) thus freeing valuable processor time.



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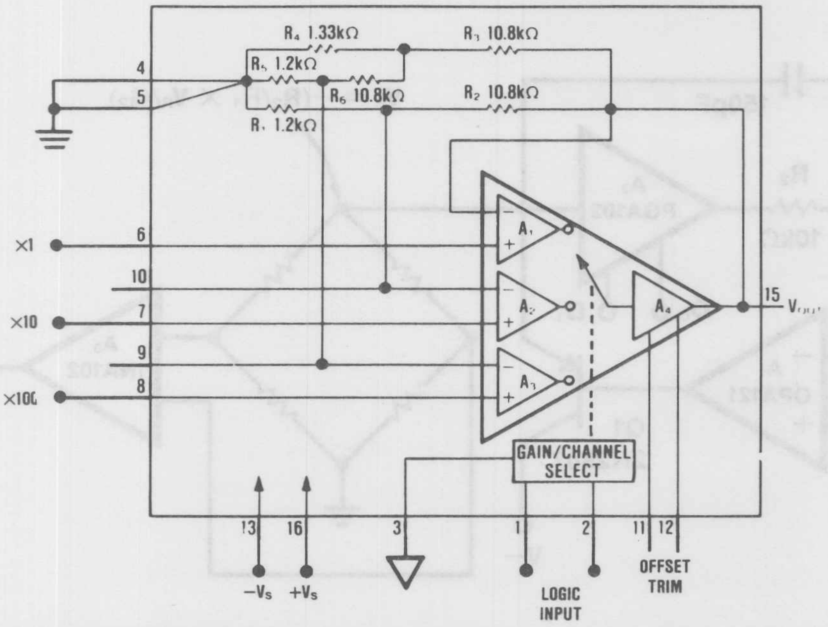
The programmable instrument amp is very useful in multiple input data acquisition systems, allowing a variety of input signals at widely differing voltage levels to be processed with high accuracy. Gains can be programmed under processor control according to the requirements of the selected channel. Alternatively, the processor can select the proper gain based on the results of an initial conversion. This achieves maximum accuracy and dynamic range. Binary gain ranges in this application makes scaling the output fast and efficient by using shift instructions in processor software.

See the MPC22,32, MPC16 and MPC800 series multiplexer products for the "front end" of this type of system.

PGA102 PROGRAMMABLE GAIN AMPLIFIER



FEATURES

- DIGITALLY-PROGRAMMABLE GAINS: ×1, ×10, ×100
- LOW GAIN ERROR: 0.01%, max
- LOW GAIN DRIFT: 5ppm/°C, max
- LOW NONLINEARITY: 0.003%, max, 14-BIT
- FAST SETTLING: 2.8μsec, 0.01%, typ
- THREE INDEPENDENT INPUT CHANNELS WITH SEPARATE GAIN ADJUSTMENT
- LOW COST
- SMALL 16-PIN DIP PACKAGE

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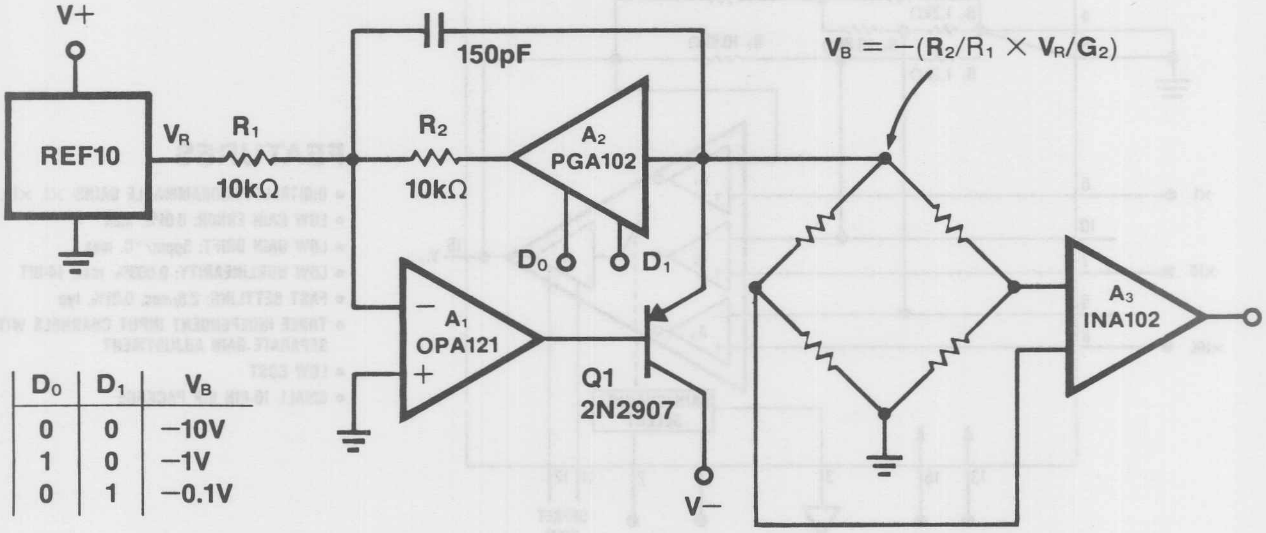
Related to the PGA200 and PGA201, the new, totally monolithic PGA102 breaks the cost barriers of previous programmable gain amplifiers*. It is a single-ended input amplifier with three inputs of differing gains--X1, X10 and X100. This provides both the ability to change gains and to switch inputs. Thus multiple signal sources of differing amplitudes can be multiplexed to a single output. A two bit word (with latch) selects the desired input/gain.

It is ideal for low cost A/D peripheral cards. The latched gain select, allow easy interfacing and provides versatility where a single card design must serve a wide variety of signal level applications.

And it's fast too!

* Burr-Brown defines "programmable gain" as digitally programmed with logic signals, not pin programmed. Other manufacturers use different terms.

PROGRAMMABLE BRIDGE EXCITATION



D_0	D_1	V_B
0	0	−10V
1	0	−1V
0	1	−0.1V

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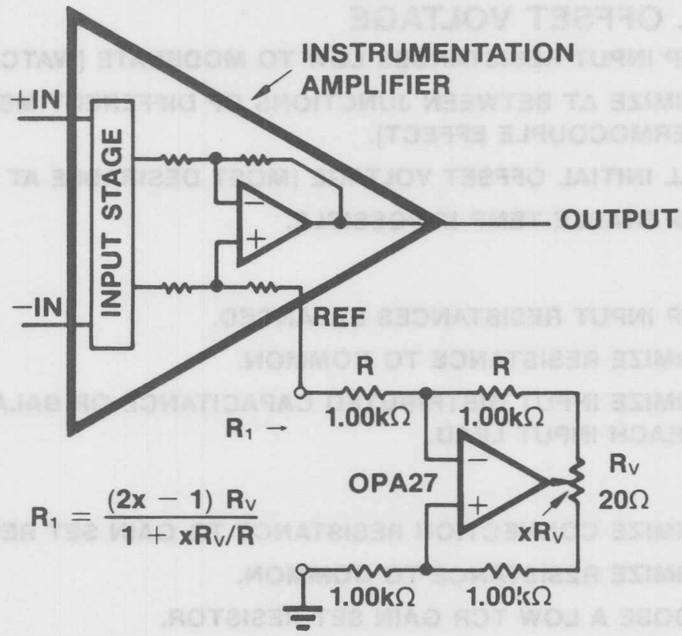
One obvious way to achieve a large conversion range with a bridge signal is to use a programmable gain element on the output of the bridge. An often overlooked alternative approach is to provide a switchable bridge excitation voltage. This avoids many pitfalls of thermal drift within the bridge elements caused by self-heating.

Low excitation levels may be programmed for supervisory or alarm functions. When accurate conversions are required, the bridge excitation can be increased momentarily to achieve maximum accuracy. This is accomplished by employing the PGA102 inside the feedback path of A1, resulting in a programmable attenuator function. Q1 provides the required current drive capability for the bridge.

"Digital gain control wins op amp a niche in microprocessor systems," Electronic Design, February 21, 1985.

CMR TRIM CIRCUIT



$$R_1 = \frac{(2x - 1)\,R_V}{1 + xR_V/R}$$

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It is sometimes necessary to make small adjustments to the common-mode rejection (CMR) of a differential amplifier. Since the instrument amp is factory trimmed for CMR, the resistance needed in series with the REFerence connection to "fine tune" the CMR might be positive or negative. The op amp circuit placed in series with the output REF pin (normally connected directly to ground) provides a small amount of adjustable positive or negative impedance necessary to accurately trim CMR.

SUGGESTIONS FOR MINIMIZING ERRORS IN IA DESIGNS

TOTAL OFFSET VOLTAGE

1. KEEP INPUT RESISTANCES LOW TO MODERATE [WATCH I_{BIAS} ERRORS]
2. MINIMIZE ΔT BETWEEN JUNCTIONS OF DIFFERENT METALS [THERMOCOUPLE EFFECT].
3. NULL INITIAL OFFSET VOLTAGE [MOST DESIRABLE AT OPERATING TEMP].
4. KEEP STABLE TEMP IF POSSIBLE.

CMR

1. KEEP INPUT RESISTANCES BALANCED.
2. MINIMIZE RESISTANCE TO COMMON.
3. MINIMIZE INPUT DISTRIBUTED CAPACITANCE OR BALANCE RC ON EACH INPUT LEAD.

GAIN

1. MINIMIZE CONNECTION RESISTANCE TO GAIN SET RESISTOR.
2. MINIMIZE RESISTANCE TO COMMON.
3. CHOOSE A LOW TCR GAIN SET RESISTOR.

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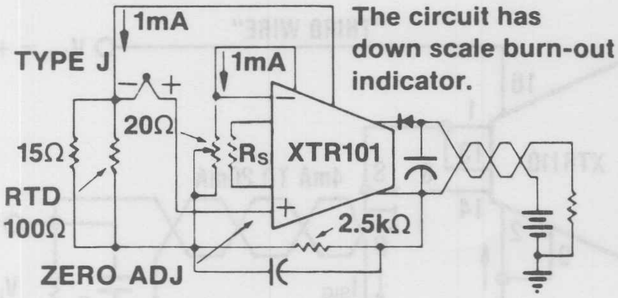
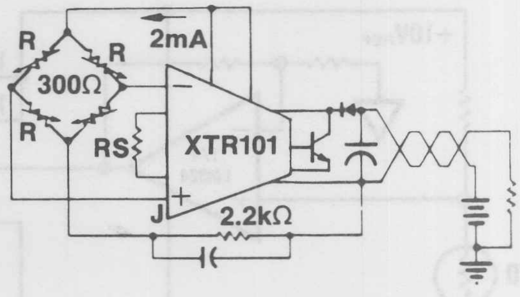
High performance instrumentation amplifiers, like high performance op amps, need careful applications circuit design and implementation to achieve their fully specified performance. This checklist outlines many of the more common pitfalls in using IA's. When you need precision performance, refer to this list to assure that you are achieving maximum accuracy.

(Many of these same points apply equally to precision op amp applications--e.g. thermocouple effects. Use the list for these applications as well.)

TWO-WIRE TRANSMITTER



Thermocouple Input with RTD Cold Junction Compensation



Bridge Input, Current Excitation

XTR101 FEATURES

- INSTRUMENTATION AMPLIFIER INPUT
  Low Offset Voltage, 25μV max
  Low Voltage Drift, 0.5μV/°C max
  Low Nonlinearity, 0.01% max
- TRUE TWO-WIRE OPERATION
  Power and Signal on One Wire Pair
  Current Mode Signal Transmission
  High Noise Immunity
- DUAL MATCHED CURRENT SOURCES
- WIDE SUPPLY RANGE, 11.6V to 40V
- −40°C TO +85°C SPECIFICATION RANGE
- SMALL 14-PIN DIP PACKAGE

ISOLATION FROM GROUND IS POSSIBLE WITH APPROPRIATE CIRCUITRY

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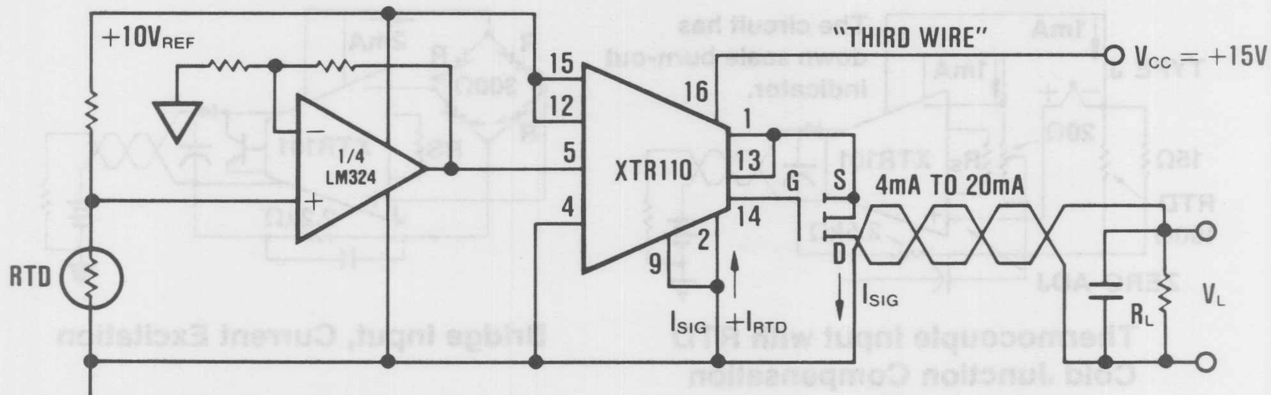
Two-wire transmitters are used to send accurate analog signals over long distances. By converting an input voltage to a current, an analog quantity may be transmitted via twisted pair without errors from voltage drops. The XTR101 uses the common 4 to 20 mA standard... 4 mA flowing in the loop indicates low scale.. 20 mA indicates top of scale input. An internal reference circuit provides the 4 mA offset.

The XTR101 is powered from the receiving end by the loop power source. A portion of the 4 mA low scale is used to power internal circuitry, thus no separate power supply is required. A resistor in series with the ground return wire senses the current flowing in the loop and is proportional to the input voltage.

Two current sources (1 mA each) are available to power external circuitry such as providing cold junction compensation (left) or exciting a bridge transducer (right). If not used, these current sources should be grounded.

The second application demonstrates the use of a outboard NPN transistor providing the path for the majority of the loop current. This optional mode of operation reduces chip dissipation (the important signal dependent portion) and improves linearity and loop power supply rejection.

BASIC THREE-WIRE TRANSMITTER



INPUT MAY BE GROUND REFERENCED

XTR110 FEATURES:

- 4mA TO 20MA TRANSMITTER
- SELECTABLE INPUT/OUTPUT RANGES:
  0V to +5V, 0V to +10V Inputs
  0mA to 20mA, 5mA to 25mA Outputs
  Other Ranges
- 0.01% MAX NONLINEARITY, 12-BIT
- PRECISION +10V REFERENCE OUTPUT
- SINGLE SUPPLY OPERATION
- CURRENT SOURCING TO COMMON
- WIDE SUPPLY RANGE, 13.5V TO 40V

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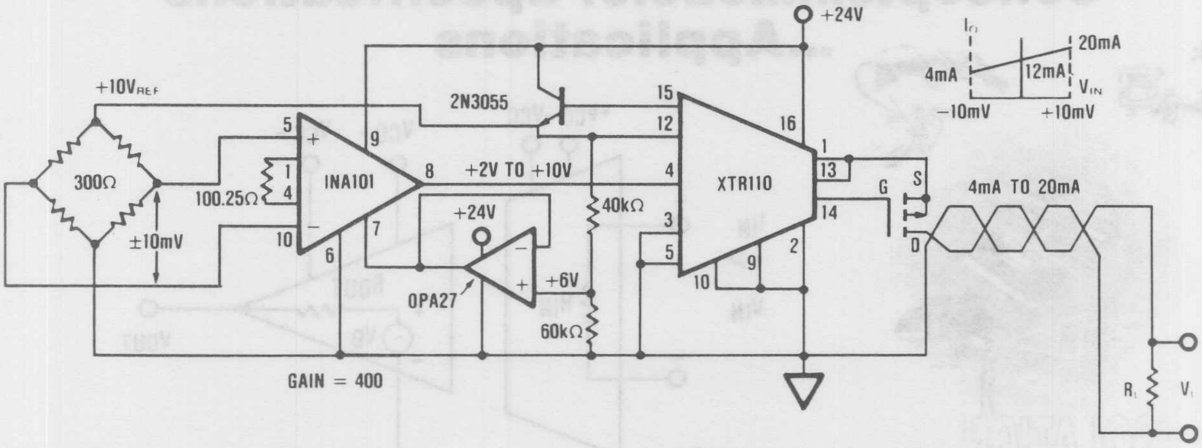
The XTR110 is a 3-wire transmitter. It converts an input voltage to an output current (0 to 20 mA, 4 to 20 mA etc.). It is powered from a single supply voltage, which may originate at the transmitter location or may be brought in from the receiving end on a third wire. Use of a separate power source makes larger currents available for use in exciting low impedance bridges or powering additional signal conditioning circuitry. It uses an external MOSFET to reduce dissipation in the XTR110 package, thus improving accuracy.

The internal 10 volt reference in the XTR110 is used to supply a current to an RTD (resistance temperature device) in this circuit. The voltage on the RTD is amplified by the LM324 which then drives the XTR110.

Note that the XTR110 is a current sourcing device. (The XTR100 is a current sinking device.)

SINGLE-SUPPLY BRIDGE TRANSMITTER



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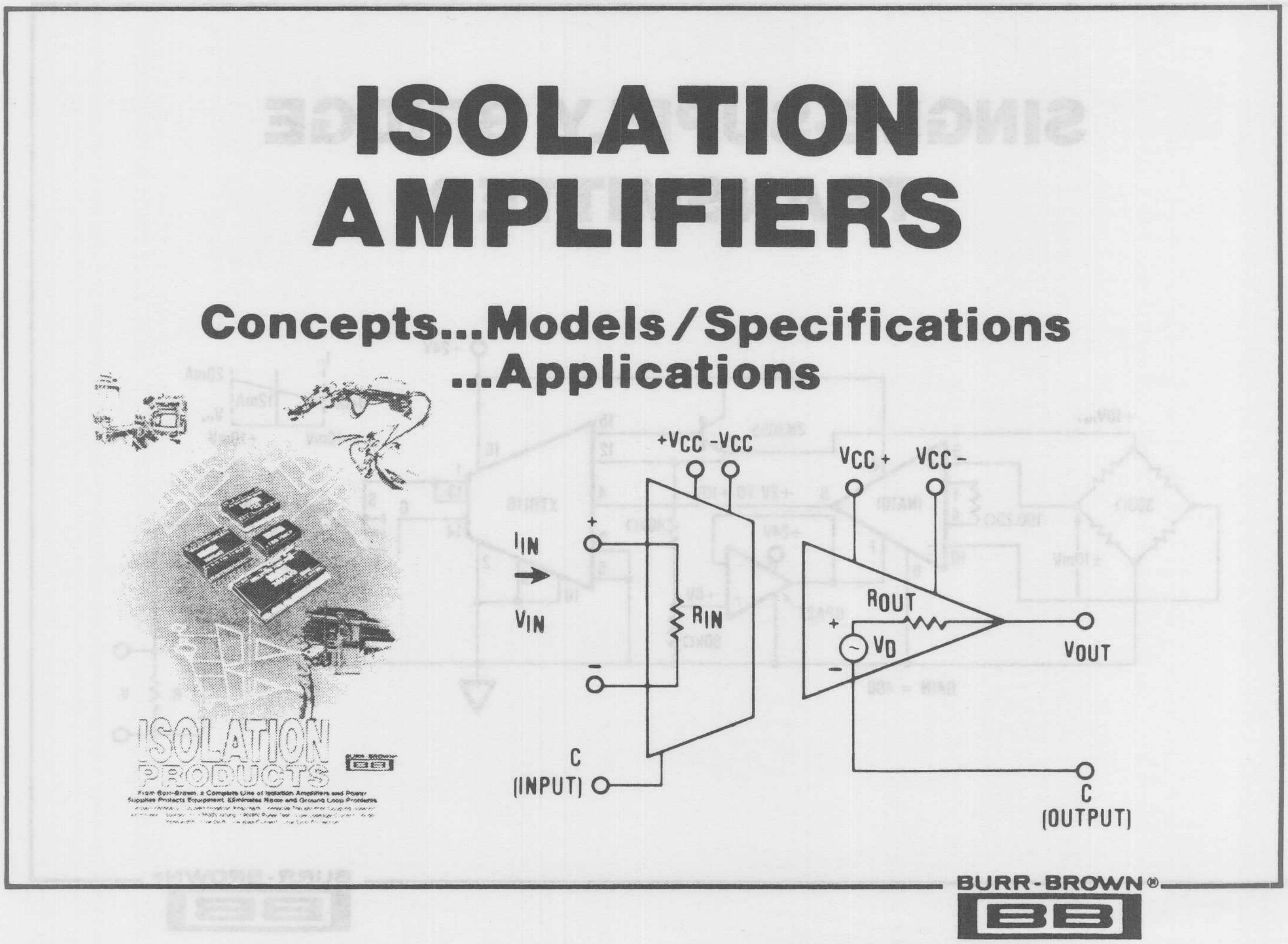
The voltage reference of the XTR110 is used in this circuit to create a "false ground" equal to 6 volts to which the INA101 output common terminal is referred. The +-4 volt output swing around this false ground then provides the required scale offset when referred to ground. This approach of offsetting ahead of the XTR110 then allows use of a precision instrumentation amp in an application which would otherwise require output swing to its negative supply.

A low-cost enhancement mode fet is used to conduct the 4 to 20 mA output current. This keeps power dissipation in the XTR110 constant with signal variations for maximum accuracy and linearity.



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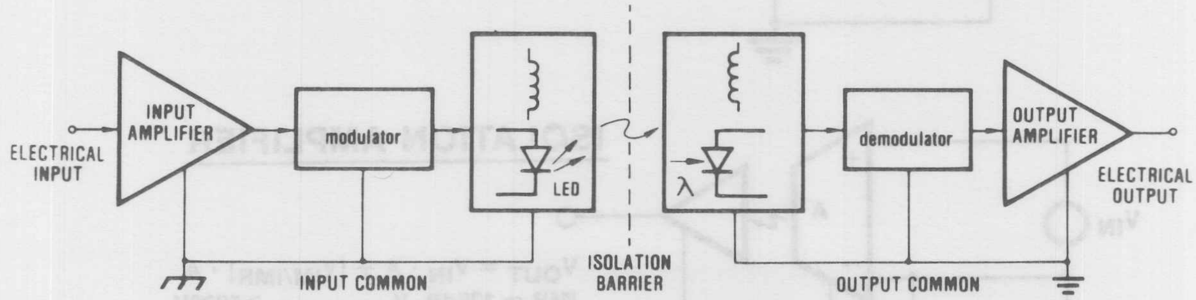
The isolation amplifier transmits an analog signal across a nonconductive barrier.

Isolation amps are used in a variety of environments including industrial, nuclear and medical applications. They are used to:

1. Protect people from electric shock.
2. Protect equipment from damage.
3. Reduce interference from unwanted voltages or noise.

ISOLATION AMPLIFIER DESIGN



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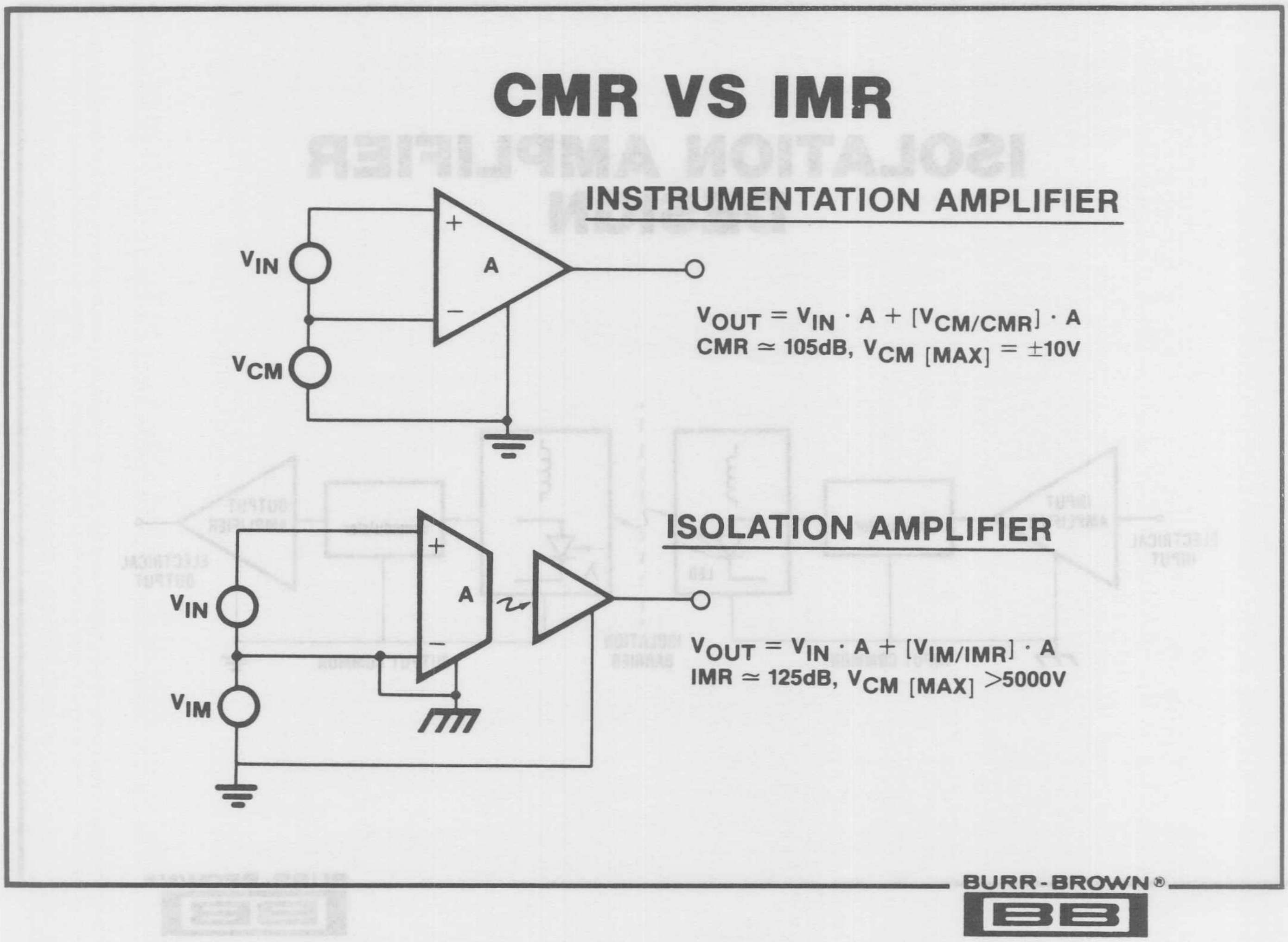
An isolation amplifier consists of a means of modulating the input signal to allow its transmission across the isolation barrier via transformer or optical coupling and a corresponding demodulator on the output side. Since feedback around the complete system would defeat the intended function of an isolation amp, high accuracy must be achieved by accurate matching of localized feedback paths.

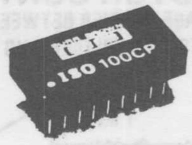


While an instrumentation amplifier uses its common-mode rejection to reject an interfering error signal, the isolation amplifier uses its isolation mode rejection to reject error sources of much higher amplitudes. The isolation mode rejection is usually much higher than the common-mode rejection of instrumentation amplifiers.

The high level of rejection of isolation mode signals leads to a class of applications not requiring isolation per se, but needing the ability to reject interfering signals.

BURR-BROWN®

ISO100



Miniature
Low Drift - Wide Bandwidth
ISOLATION AMPLIFIER

FEATURES

- EASY TO USE, SIMILAR TO AN OP AMP
  $V_{OUT}/I_{IN} = R_F$, Current Input
  $V_{OUT}/V_{IN} = R_F/R_{IN}$, Voltage Input
- 100% TESTED FOR BREAKDOWN
  750V Continuous Isolation Voltage
- ULTRA-LOW LEAKAGE, 0.3μA, max, at 240V/60Hz
- WIDE BANDWIDTH, 60kHz
- LOW COST
- 18-PIN DIP PACKAGE

APPLICATIONS

- INDUSTRIAL PROCESS CONTROL
  Transducer sensing
  (thermocouple, RTD, pressure bridges)
  4mA to 20mA loops
  Motor and SCR control
  Ground loop elimination
- BIOMEDICAL MEASUREMENTS
- TEST EQUIPMENT
- DATA ACQUISITION

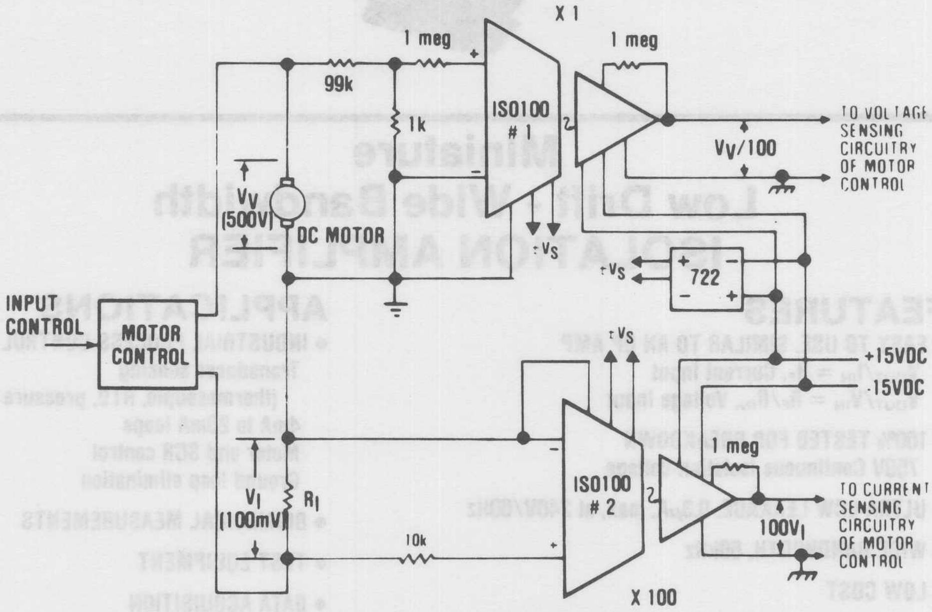
BURR-BROWN®

The ISO100 isolation amplifier is an optically coupled design capable of signal bandwidths up to 60kHz. Its isolation voltage rating of 750 volts (continuous) makes it suitable for a majority of industrial applications. Packaged in an 18 pin DIP package, the ISO100 is the smallest commercially available isolation amplifier.

In contrast to the 3656, the ISO100 does not have an internal isolated power supply. Many industrial systems have power available on both sides of the isolation barrier obviating the need for this function. For other applications, the model 722 or 724 isolated power supplies are appropriate choices.

MOTOR CONTROL

ISOLATION AMPLIFIERS PUT A VOLTAGE BARRIER BETWEEN DRIVING CIRCUITRY FOR THE MOTOR AND THE CIRCUITS FOR VOLTAGE AND CURRENT SENSING.



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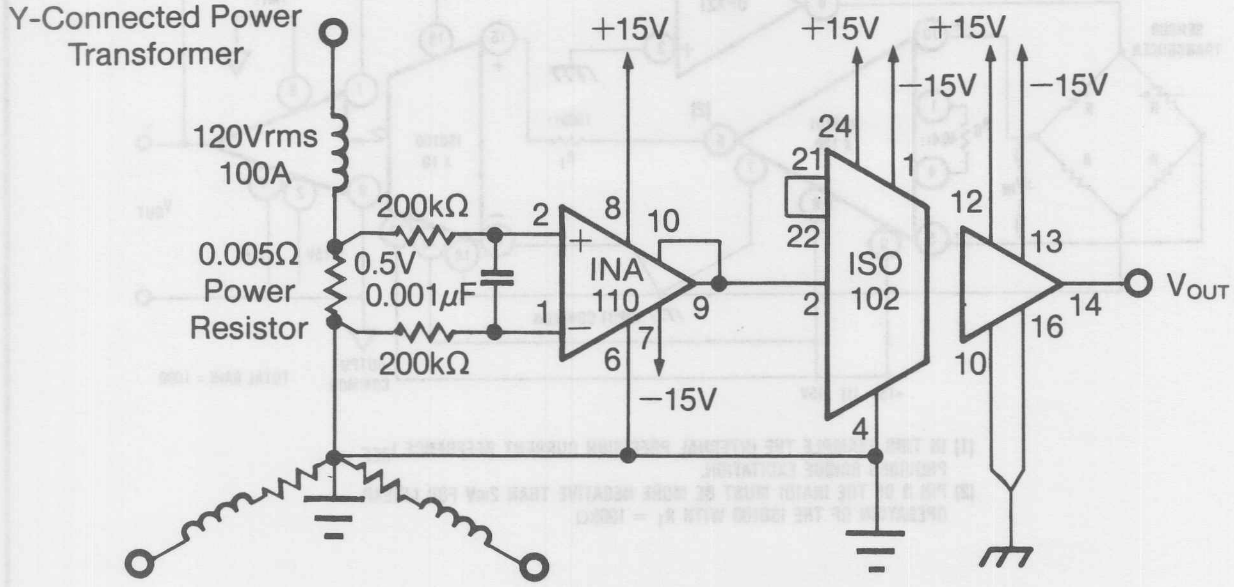
Industrial control applications often must sense voltages and currents which are referenced to differing potentials. The ISO100 miniature isolation amplifiers in this circuit are powered by the model 722 dual isolated power converter. Two distinct isolated channels (input-to-output and channel-to-channel isolation) are used to sample voltage and current of a high torque DC motor. The results are then used to compute power in a closed-loop control system.

Isolated Power Line Monitor (0.5μA leakage current at 120Vrms.)



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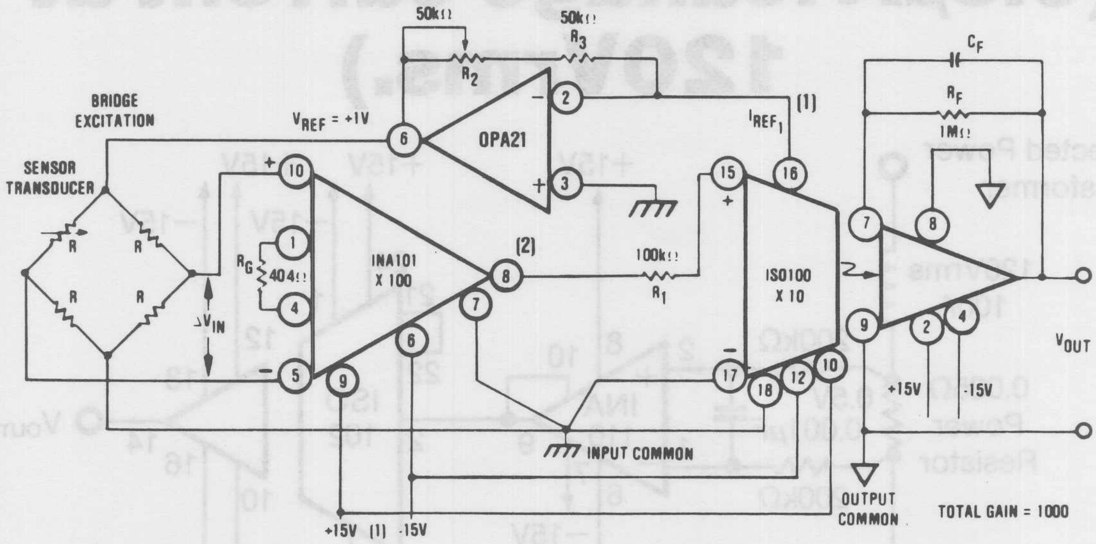
Monitoring power line currents can be accomplished accurately using an instrumentation amplifier that senses just the power resistor voltage. This technique prevents wiring errors from interfering with the measurement.

The two input resistors protect the input amplifier should the power resistor open. Under this condition, the full power voltage appears on the plus amplifier input lead. To prevent damage to semiconductors, which can tolerate only 20V, two large input resistors are added to the FET input of the INA110. The INA110 is internally protected, and therefore, no clamping diodes are necessary. The differential capacitor rolls off the response to reject high frequency spikes above 400Hz. Because the input has very low bias current, DC errors from Ib x Rsource are negligible.

The isolation amplifier, ISO102, breaks the ground connection from the power circuit to the output instrumentation circuit. Vout is, thus, free from noise due to ground loops.

PRECISION BRIDGE ISOLATION AMPLIFIER (UNIPOLAR)



(1) IN THIS EXAMPLE THE INTERNAL PRECISION CURRENT REFERENCE I_{REF} PROVIDES BRIDGE EXCITATION.

(2) PIN 8 OF THE INA101 MUST BE MORE NEGATIVE THAN 2mV FOR LINEAR OPERATION OF THE ISO100 WITH $R_1 = 100k\Omega$

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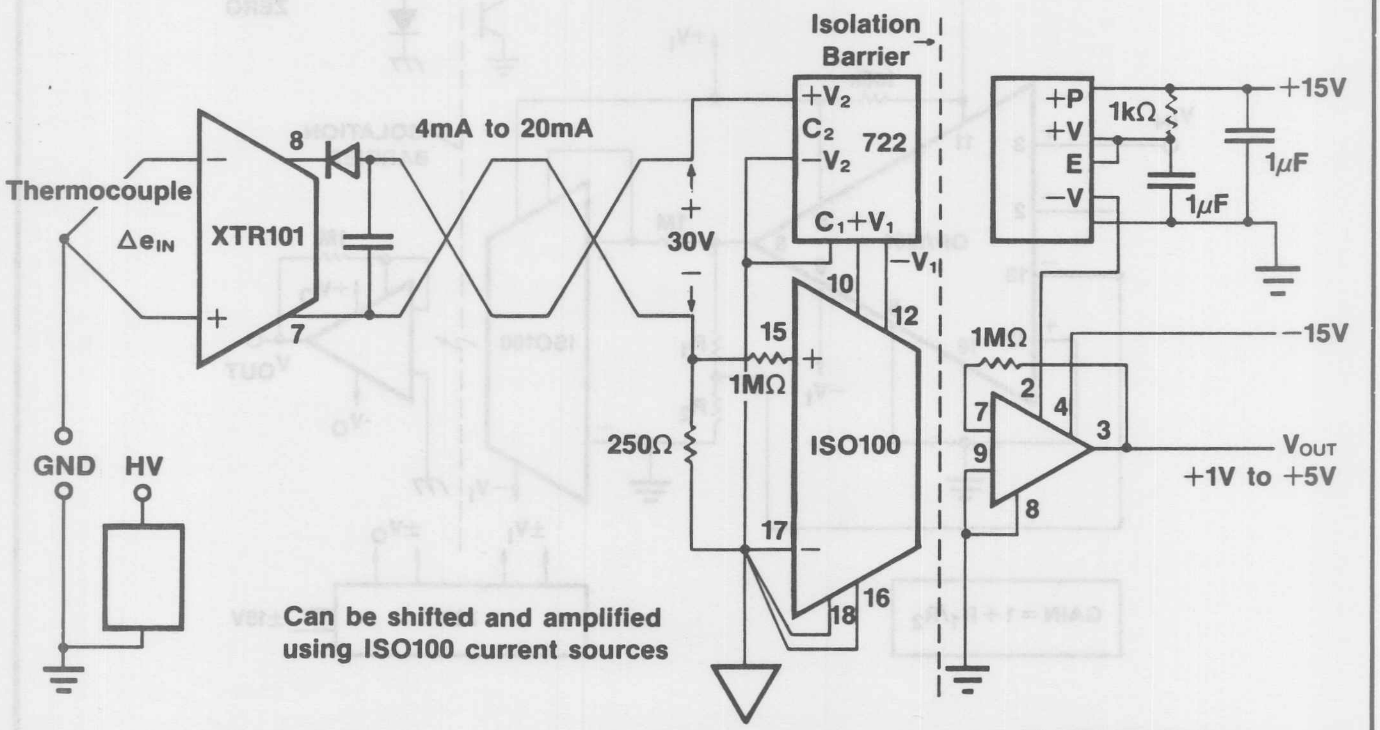
The ISO100 is functionally designed as a unipolar, current input device. A reference current is provided on pin 16, however, which allows offsetting the input to allow bipolar input currents. See application note AN-126 for details.

This circuit demonstrates another possible use of the reference, in this case to excite a bridge transducer. The current is converted to a voltage with the OPA21 low power op amp and the resulting stable voltage is used to drive the bridge. An INA101 instrumentation amp is used to accurately amplify the bridge output ahead of the ISO100 input. Preamplification of the input signal ahead of the isolation amp assures highest accuracy.

ISOLATED TWO-WIRE CURRENT LOOP



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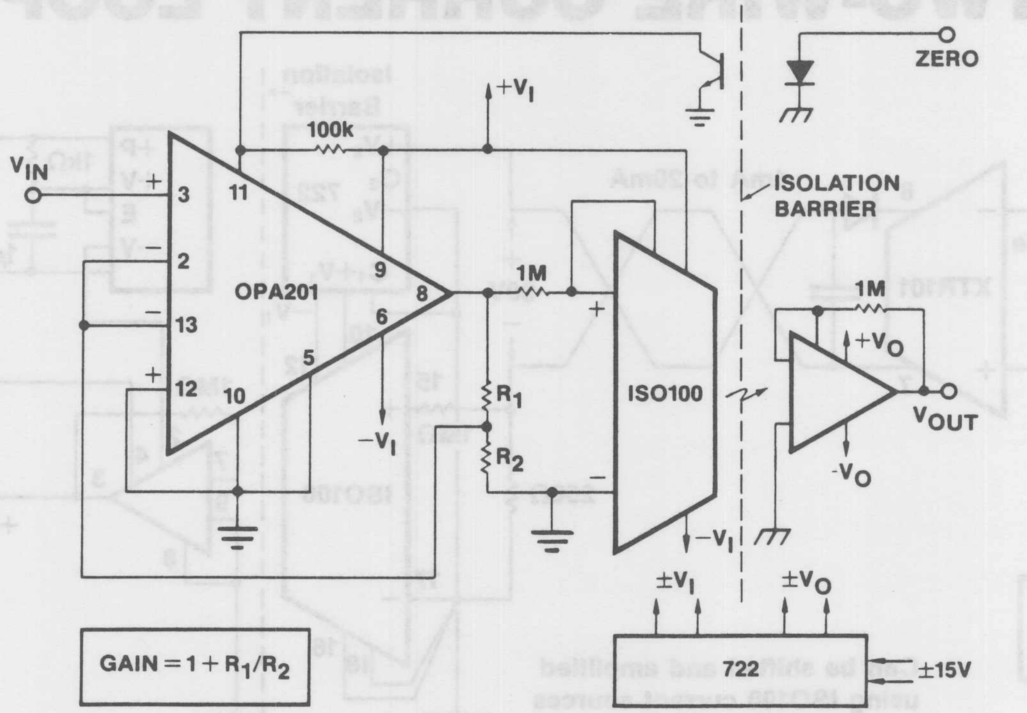
Current loop systems often additionally require voltage isolation for safety and noise reduction. Here an XTR101 current loop transmitter is combined with the ISO100 to achieve a totally isolated system. The instrumentation amplifier input serves as an ideal input for the low level thermocouple source. The current loop then sends the resulting amplified signal as a current... thousands of feet if required. The 250 ohm resistor serves as a negative side load sense. The resulting 1 to 5 volt signal is the input to the ISO100. The model 722 isolated power supply provides power to both sides of the isolation barrier.

BIPOLAR, AUTO-ZERO ISO AMP



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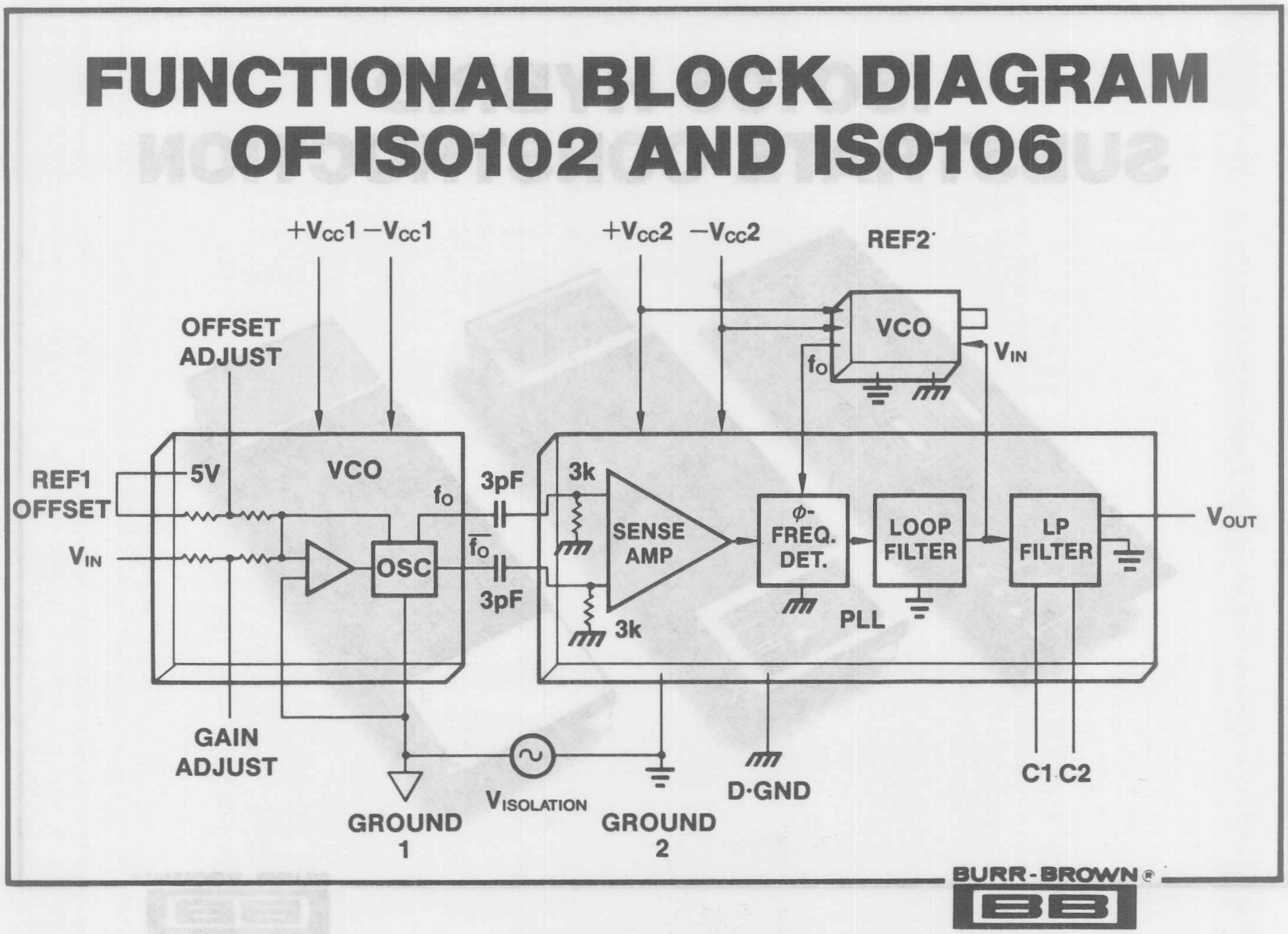
Due to the inability to apply direct voltage feedback around an isolation amplifier, errors from offset and drift are larger than encountered with typical op amp circuits. Auto-zero techniques, however, provide a viable means of achieving higher precision. Here, the OPA201 SWOP AMP is used to sample the output voltage with zero input voltage. This value could then be stored and subtracted from the measurement of Vin. Although the OPA201's inputs have slightly different input offsets, this differential offset is very small compared to the offsets in the isolation amp. This technique can then provide large improvements in accuracy.

The OPA201's low quiescent current makes it particularly suitable for isolation applications where supply current is often limited.

"Multiplexed inputs on op amp simplify a variety of circuits," EDN, January 12, 1984.

"The SWOP Amp," Burr-Brown applications note AN-127.

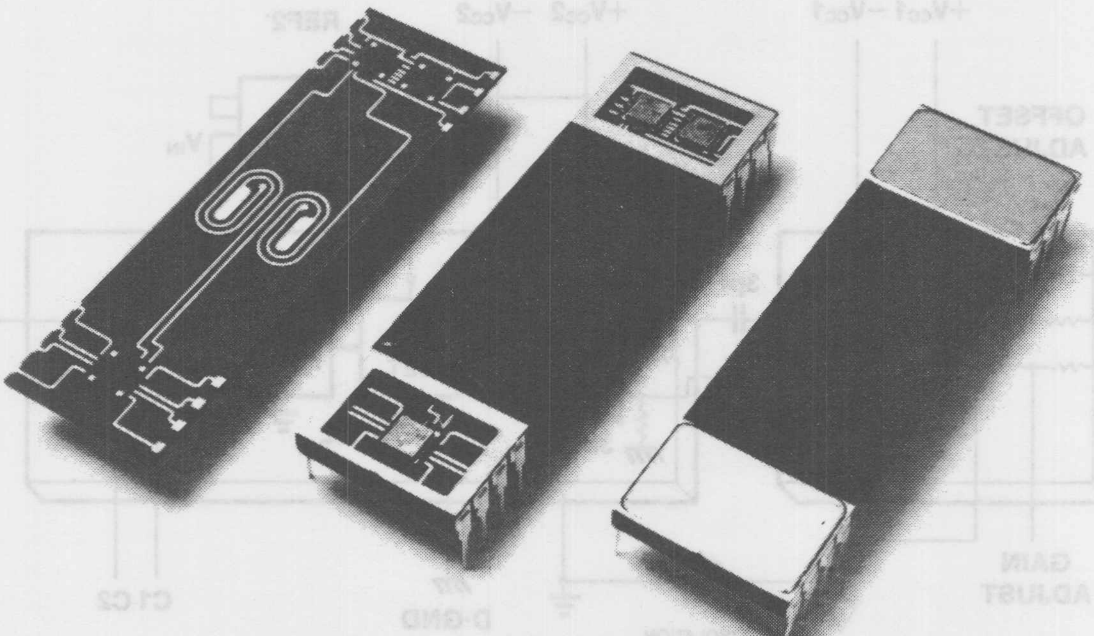


The ISO102 and ISO106 uses a proprietary voltage to frequency converter on the input side which converts a -10 to +10 volt input signal range to frequency pulses ranging from 0.5 to 1.5 MHz. The frequency pulses are generated in complimentary form, fo and fo inverted. This signal pair is coupled across the isolation barrier with two very low value capacitors.

On the output side of the isolation barrier, a proprietary chip senses the frequency signal and reconstructs logic level pulses. This chip also contains the necessary components to form a phase-locked-loop in conjunction with a second VCO chip. This second VCO chip is carefully matched with the VCO on the input side by selecting adjacent die on a single wafer and by careful laser trimming. Through this careful matching, the input to output transfer function is made to be very linear and drift free.

Interfering isolation voltages are rejected by the use of the complimentary signal transmission across the barrier. An AC interfering signal creates a small AC voltage at both inputs of the sense amp. This is a common mode signal, however, and is easily rejected by the sense amp. As long as the common mode range of the sense amp is not exceeded, signal transmission remains unscathed. The rate of change of the interfering isolation signal must exceed 500 V/us to impair signal transmission.

ISO106 HYBRID SUBSTRATE CONSTRUCTION



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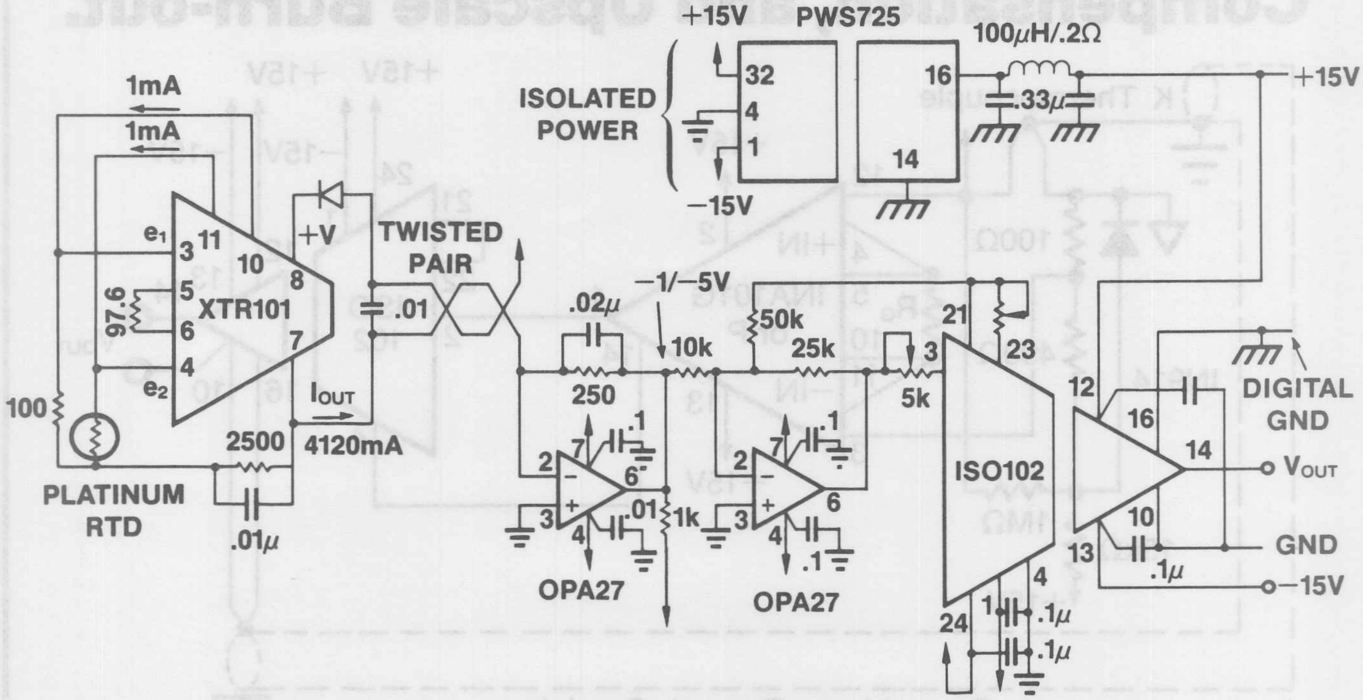
The ISO102 and ISO106 (shown here) isolation amplifiers are constructed on a special multilayer substrate. The first layer shows the two signal coupling capacitors which are formed by interleaving spiral-wound traces. The fringe effect capacitance between the two traces is approximately 3 pF.

The base layer is fired with a second layer of ceramic which hermetically seals the input side of the barrier from the output side and from the external environment.

Separate cavities on the package ends house the chips--the VCO chip on the input side, and a VCO chip plus the sense amp/phase-locked-loop chip on the output side.

REMOTE ISOLATED THERMOMETER



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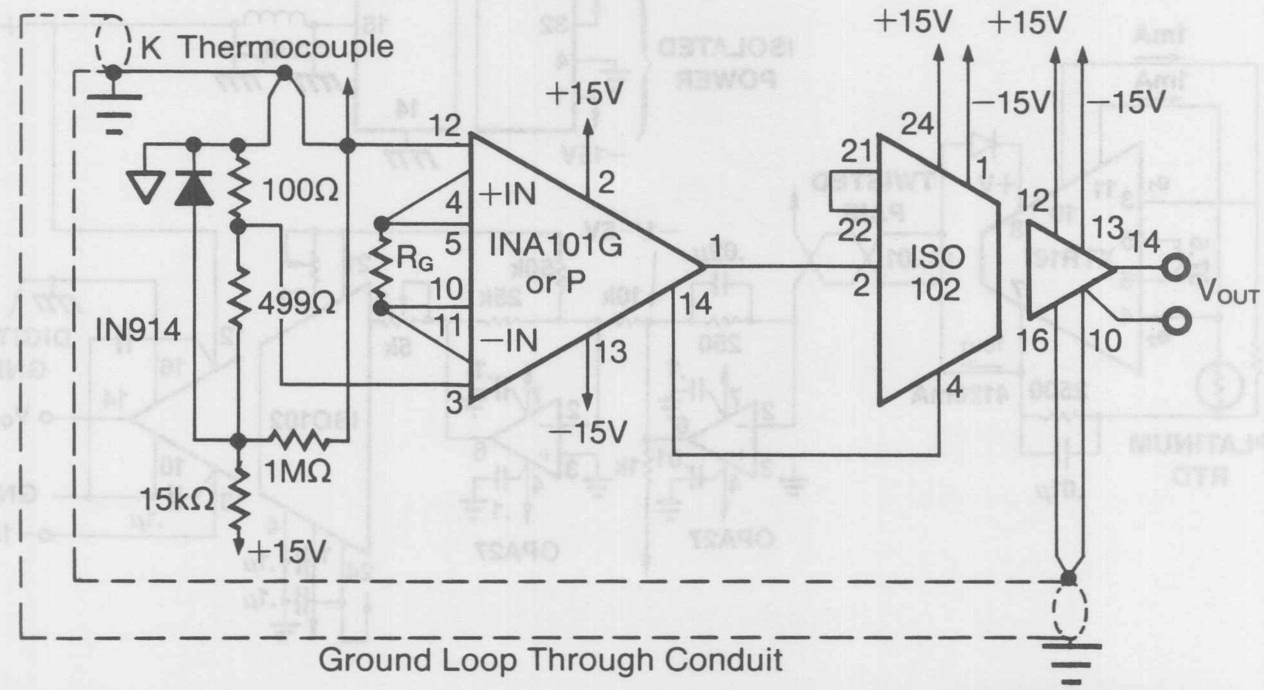
Many process control applications involve measurement of physical parameters such as temperature and signal transmission to a central receiving point. Often, the various signal channels must be isolated from each other as well as from input to output. This avoids the problems of safety and variable ground drops in such a large system.

The circuit shown uses an XTR101 voltage input to two-wire transmitter to amplify the voltage across a platinum RTD (Resistance Temperature Device) and convert it to a 4 to 20 mA current. The current is transmitted via twisted pair to an OPA27 configured as a current to voltage converter. The voltage is then applied to the ISO102 and moved across the isolation barrier.

A model PWS725 isolated power supply provides power to the input side of the barrier. The PWS725 is scheduled for introduction in March of 1987.

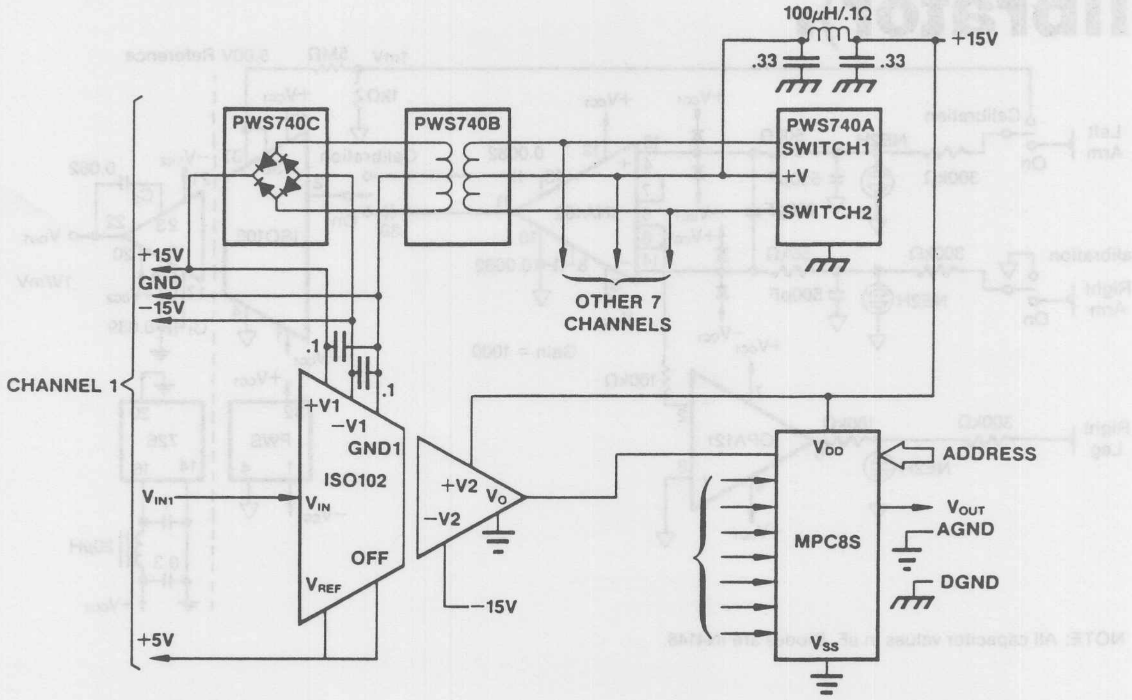
Thermocouple Amplifier with Ground Loop Elimination, Cold Junction Compensation, and Upscale Burn-out.



Ground loops plague many measurement systems. One technique to reduce errors and noise is to utilize an instrumentation amplifier which amplifies input signal difference but rejects interferring common-mode voltages. By adding an isolation amplifier, even higher rejection can be obtained. In fact the thermocouple shown can be connected to a high voltage, within the rating of the isolation amplifier, and no damage will occur to the following stage, such as a computer or meter.

The INA101 circuit is accomplishing three tasks here. First, it amplifies the differential thermocouple voltage. Second, it subtracts out a reference voltage established by the resistor divider connected across the diode. This establishes a cold junction compensation which is a reference to the ice point at 0 degrees centegrade. Therefore, the thermocouple voltage is always amplified relative to the temperature dependent diode voltage. Third, the +15V supply voltage will be applied to the non-inverting input should the thermocouple become an open circuit. This causes the output voltage to go to the positive rail (up-scale) indicating a burn-out condition. The unity gain isolation buffer passes this out-of-range level to its output.

LOW-COST EIGHT-CHANNEL ISOLATION



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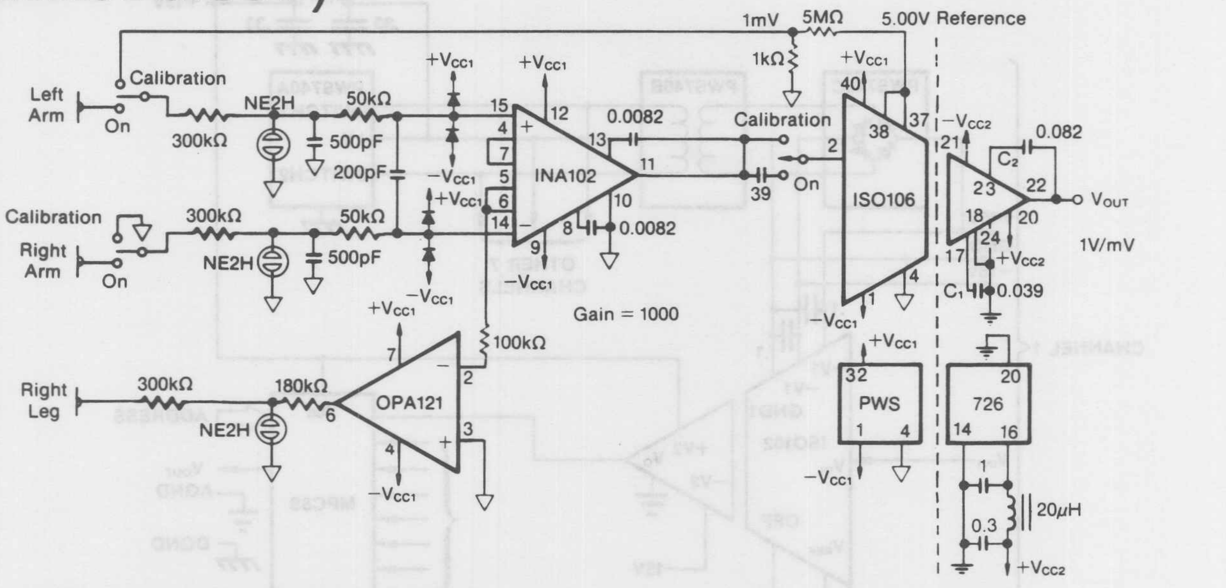
A key to achieving low cost per channel in multiple channel applications is the power supply circuitry. Each channel requires a separate power supply for channel-to-channel isolation.

The PWS740 series of power supply components is designed to fulfill this requirement. The PWS740A is a Transformer driver circuit which is capable of driving eight PWS740B transformers in parallel. Output of each transformer is rectified by a PWS740C high frequency, low loss rectifier circuit. The switching frequency is made high, so the 0.1uF bypass capacitors for the ISO102s provide the required filtering of the rectified waveform.

Right-Leg Driven ECG Amplifier (with defibrillator protection and calibrator).



NOTE: All capacitor values in μF. Diodes are IN4148.

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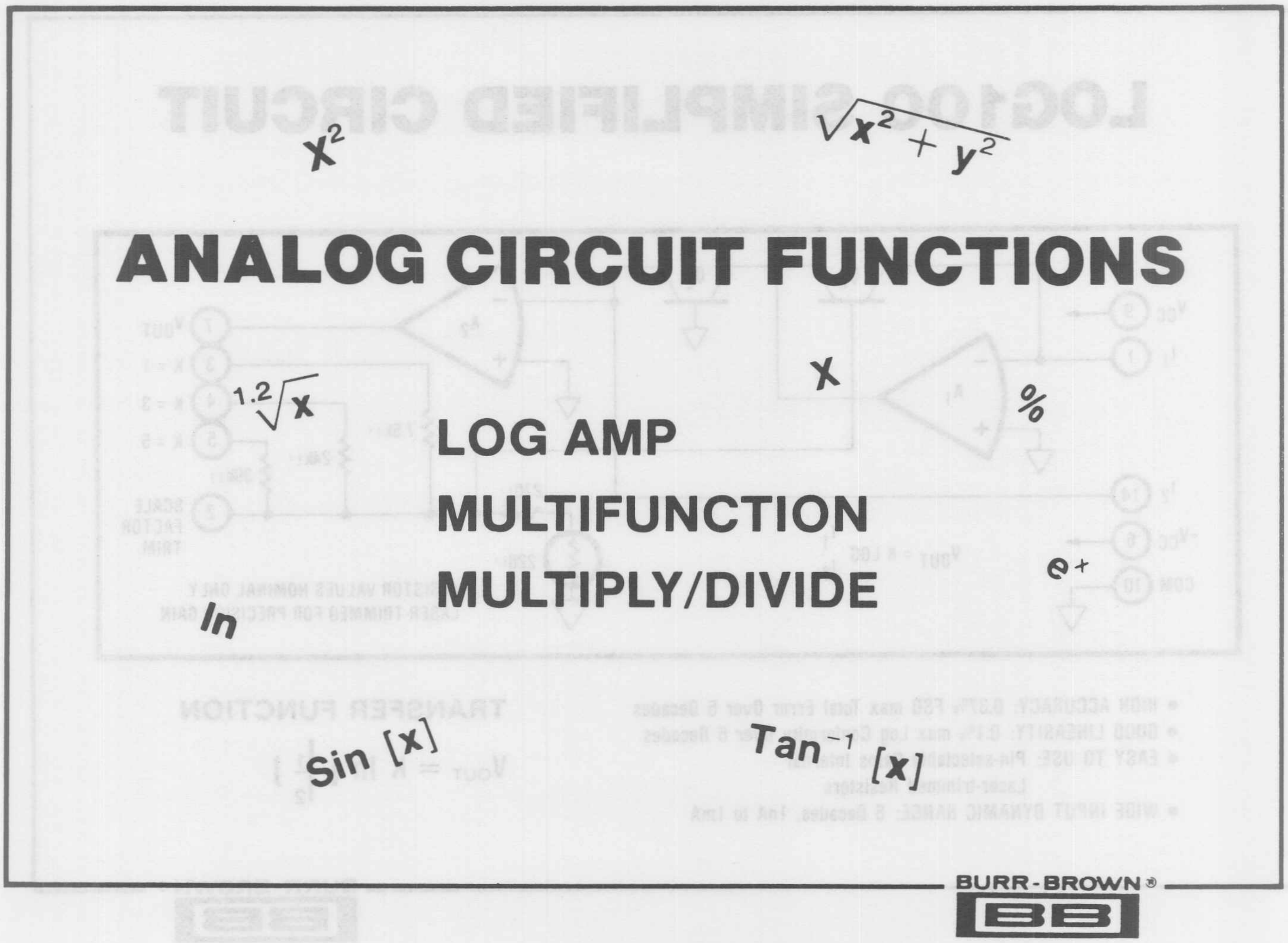
Successfully detecting electrophysiological signals, such as electrical activity from the human heart, requires a circuit that has high gain and high common-mode voltage rejection. The instrumentation amplifier, INA102, pin strapped to a gain of 1000, amplifies the 1mV signal difference between the right arm (with respect to the right leg) and the left arm (with respect to the right leg). The OPA121 inverts and amplifies the common-mode signal on both arms and applies it to the right leg. The object is to apply a voltage that nulls the common-mode voltage on the body. This technique adds more than 40dB of 60Hz rejection to the already high 90dB of the INA102. Also leakage current, flowing through the body, will be reduced to fractions of a microamp. Without the right leg drive, leakage can be several microamps or more.

Isolation is accomplished by using an amplifier which passes the amplified ECG signal (about 10Vp-p) across a galvanically isolated barrier. Conveniently, the ISO106 provides a +5V reference that, when attenuated, presents a 1mV calibration signal to the input.

Neon bulbs or fast diodes are used to prevent the 5000V peak defibrillation pulse (used to smooth out a grossly irregular heat beat) from damaging the INA102 and the input stage of the isolation amplifier. Under fault conditions, such as a patient limb touching ground, this high voltage can be applied across the isolation barrier. With a properly rated barrier no damage to patient or equipment occurs.



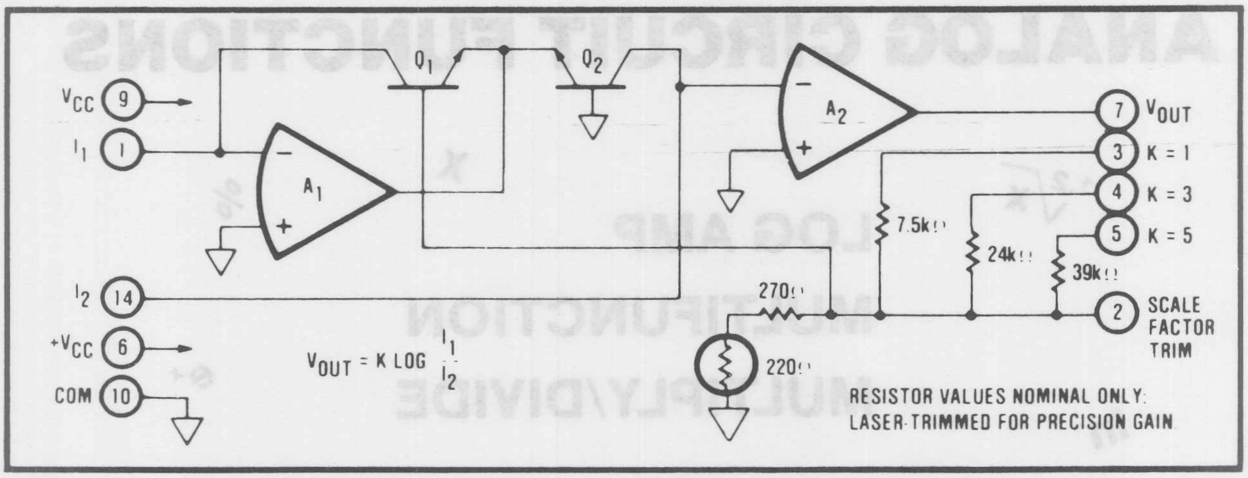
In spite of the ease with which nonlinear functions can be generated in software, analog techniques still prove to be an economical and functionally attractive alternative.

Available functions include:

- Multipliers
- Dividers
- Log Amps
- Transcendental Functions
- Power Series Approximations

Systems requiring conversions at even moderate speed can severely tax the processing power of a micro or larger computer leaving analog techniques as the only viable approach.

LOG100 SIMPLIFIED CIRCUIT



- HIGH ACCURACY: 0.37% FSO max Total Error Over 5 Decades
- GOOD LINEARITY: 0.1% max Log Conformity Over 5 Decades
- EASY TO USE: Pin-selectable Gains Internal Laser-trimmed Resistors
- WIDE INPUT DYNAMIC RANGE: 6 Decades, 1nA to 1mA

TRANSFER FUNCTION

$$V_{OUT} = K \ln\left(\frac{I_1}{I_2}\right)$$

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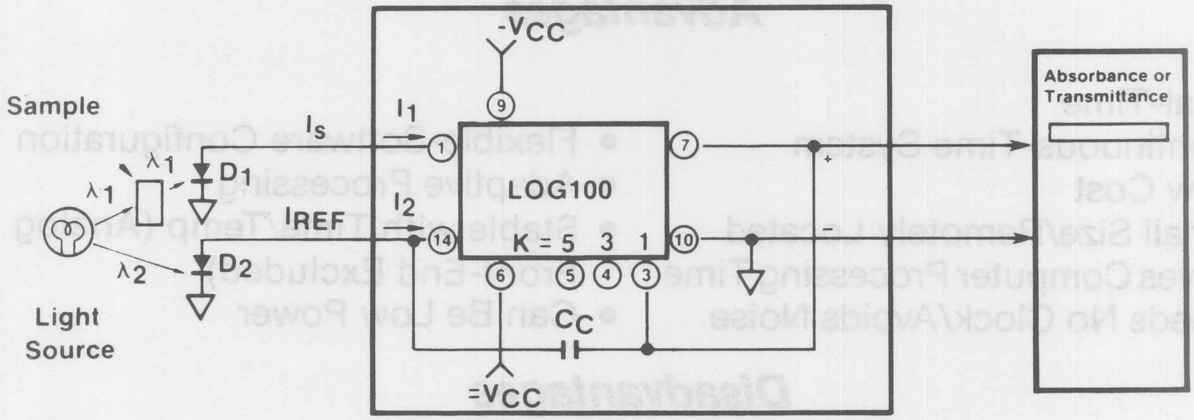
The LOG100 uses the logarithmic characteristic of a silicon junction to accurately create a logarithmic transfer characteristic. Since the junction equation

$$Vbe = Vt * \ln(Ie/Is) \qquad \text{where } Vt = kT/q$$

contains an obvious temperature dependence, the accuracy of the LOG100 over temperature depends on careful implementation and trimming of a thermistor compensation circuit.

ABSORBANCE MEASUREMENT USING LOG RATIO



V_{out} is a logarithmic function of input current ratio

$$V_{out} = K \log_{10} \frac{I_1}{I_2} = K \log_{10} \frac{I_{sample}}{I_{REF}} = -\text{Absorbance}$$

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Absorbance measurement is performed by splitting a light beam from a single source and directing one path through a sample of material to an optical detector, the other path passes directly to a detector and serves as a reference. The ratio of the outputs from the optical detectors describes the sample's absorbance. Furthermore, absorbance is defined as the logarithm of this ratio... a mathematical task easily performed by the LOG100 logarithmic amplifier.

This is very similar to another computation more familiar to electronics, the conversion of a voltage or current ratio to decibels (another common use of the LOG100).

The LOG100 logarithmic converter is also useful in a signal processing systems requiring accurate compression of analog data.

Comparison

Advantages

Analog Signal Processing

- Real-Time
- Continuous-Time System
- Low Cost
- Small Size/Remotely Located
- Saves Computer Processing Time
- Needs No Clock/Avoids Noise

Digital Signal Processing

- Flexible-Software Configuration
- Adaptive Processing
- Stable with Time/Temp (Analog Front-End Excluded)
- Can Be Low Power

Disadvantages

Analog Signal Processing

- Dedicated, Not Easily Reconfigured
- Initial Error-Fixed/Adjust To Zero
- Error Drifts With Time/Temp
- Requires Analog Design Engineer

Digital Signal Processing

- High Cost and Complexity
- Non-Real Time
- Can Be Computer Time-Intensive
- More Difficult Field Troubleshooting

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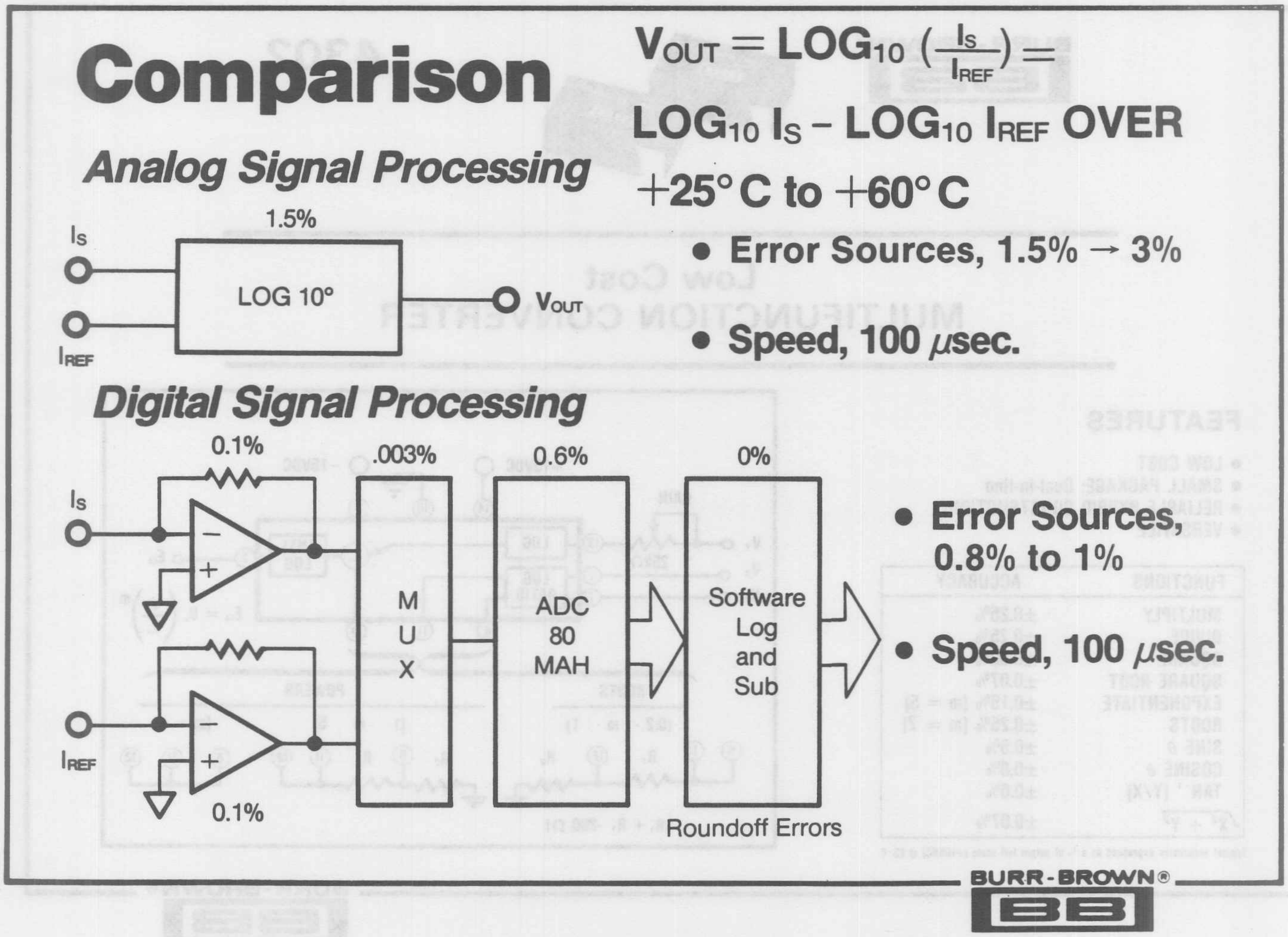
Modern signal processing use both analog and digital techniques.

There are advantages to both. The analog approach is real-time, continuous, and its low cost and small size permit it to be used in remotely located areas such as thermocouple wells. The digital approach is flexible, adaptive, and relatively stable with temperature.

There are disadvantages to both. Analog circuits are dedicated, may have higher errors especially with temperature, and often require a (rare breed) analog engineer to design functional solutions (unless ones uses Burr-Brown analog components). Digital circuits have high cost, high complexity, are not real time, and often require considerable computer time to produce an answer.



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An important element in deciding whether to use analog or digital processing circuits is "error analysis." Consider a log ratio measurement. The analog approach uses one logarithmic amplifier with a total accuracy over a temperature of +25 to +60 degrees centigrade of 1.5% to 3.0% depending on the current range. The digital approach uses not only an analog front-end but lots of registers and logic under software control. The total accuracy can be better than analog, about 0.8% to 1%. The speed may be similar, but digital can be much slower depending on analog front-end, clock speed, and acquisition time of the A/D converter.

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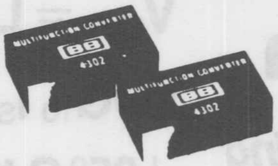
4302



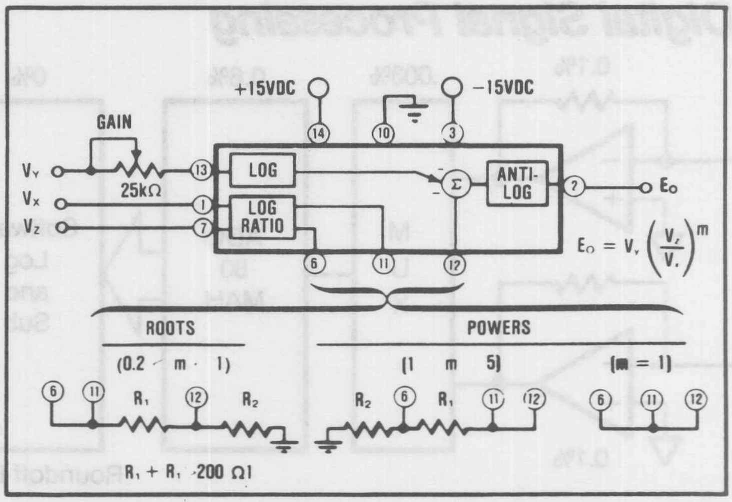
Low Cost
MULTIFUNCTION CONVERTER

FEATURES

- LOW COST
- SMALL PACKAGE: Dual-in-line
- RELIABLE HYBRID CONSTRUCTION
- VERSATILE

FUNCTIONS	ACCURACY
MULTIPLY	±0.25%
DIVIDE	±0.25%
SQUARE	±0.03%
SQUARE ROOT	±0.07%
EXPONENTIATE	±0.15% (m = 5)
ROOTS	±0.25% (m = 2)
SINE θ	±0.5%
COSINE θ	±0.8%
TAN^{-1} (Y/X)	±0.6%
$\sqrt{X^2 + Y^2}$	±0.07%

Typical accuracies expressed as a % of output full scale (+10VDC) at 25°C



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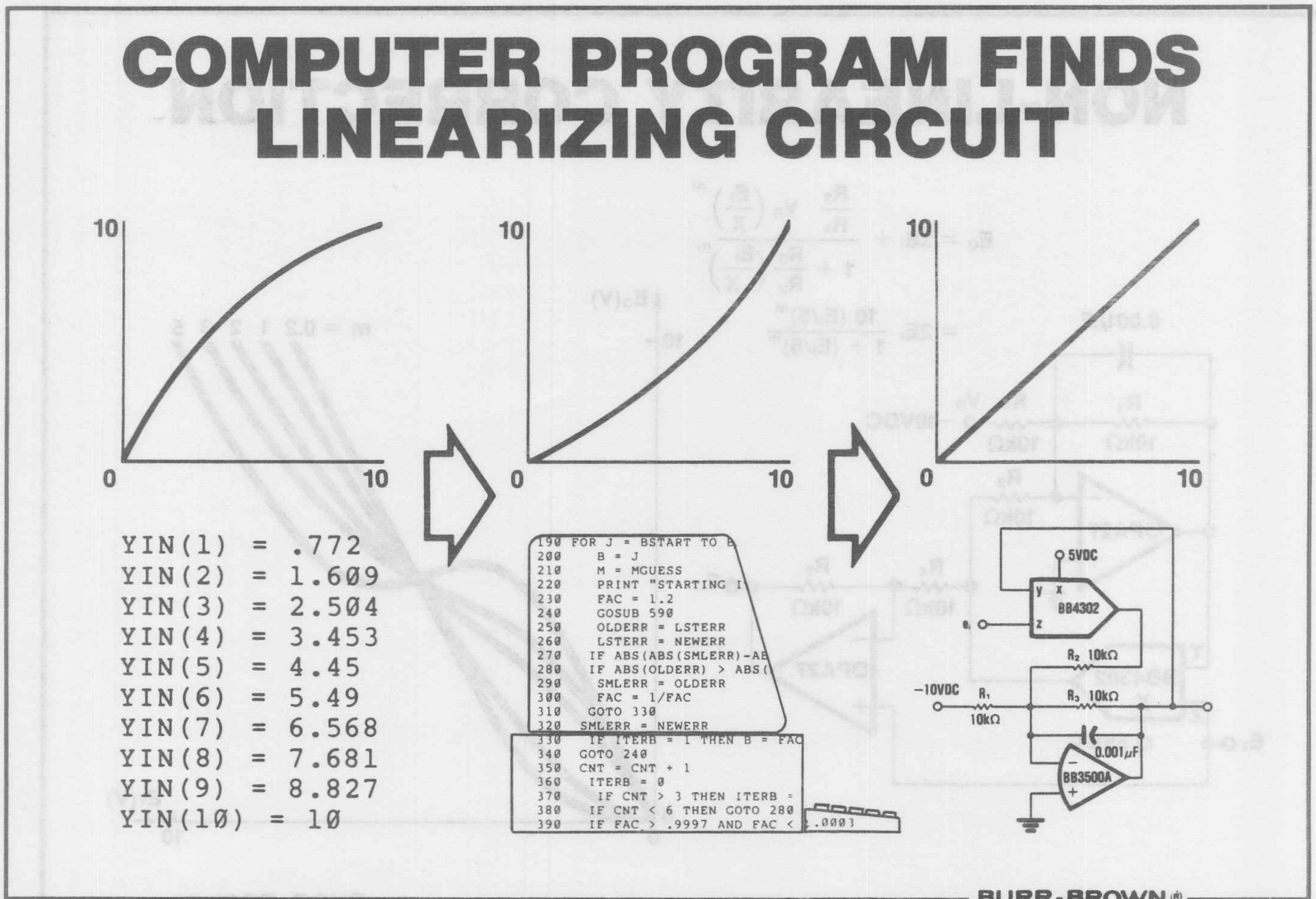
A wide variety of nonlinear response shapes may be created using the 4302 multifunction converter. The use of noninteger exponents, m, in its transfer function

$$Eo = (Vz/Vx)^m$$

allows unique flexibility in generating nonlinear responses. When combined with external op amps and used within feedback loops an even wider range of functions may be created.



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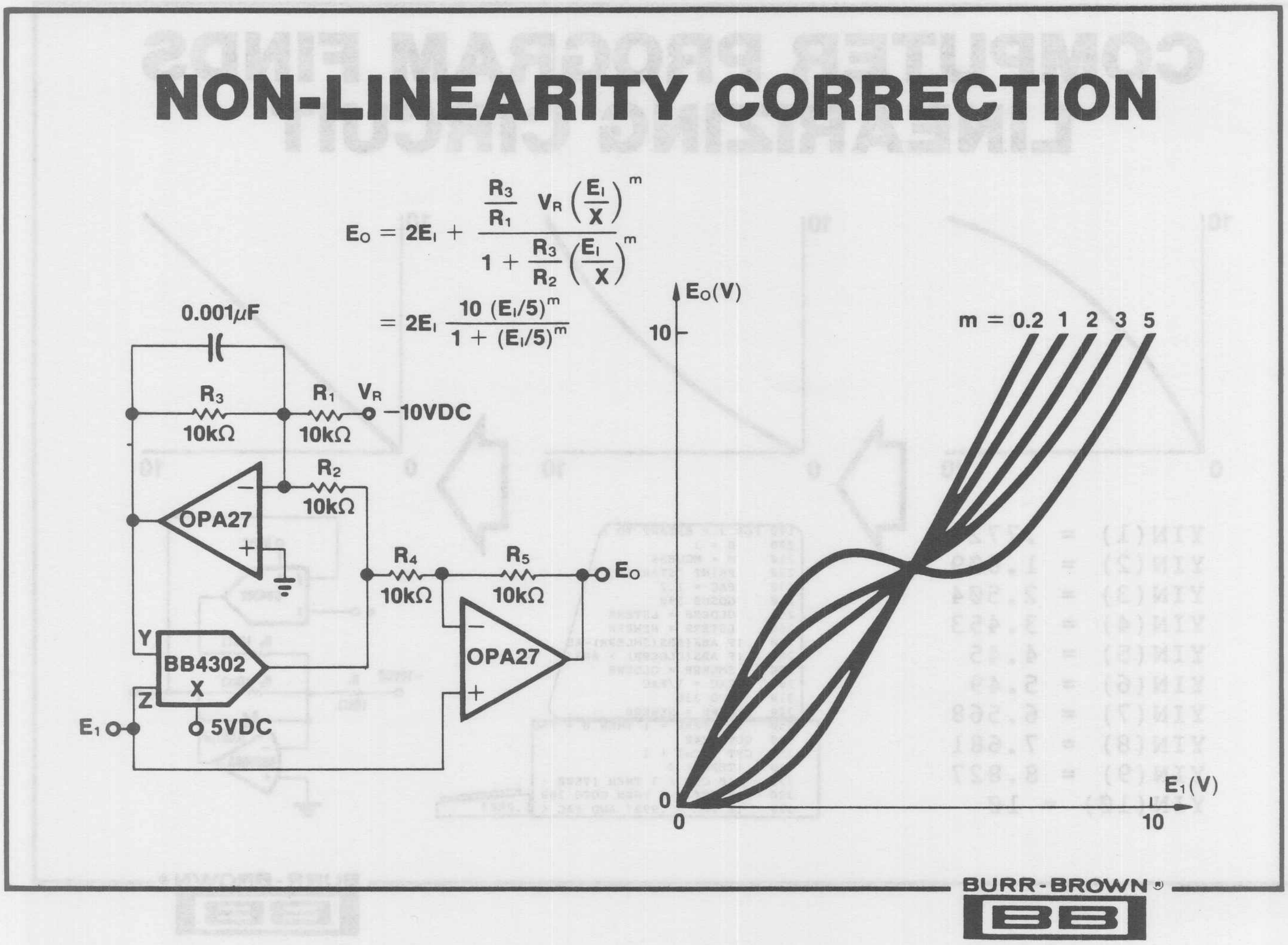
Application note AN-128 outlines a procedure for correcting nonlinearity of a sensor or system. Several circuit configurations are given with families of plots of the resulting response. A BASIC program is provided which accepts a table of nonlinear points and finds circuit parameters producing a linear output. Using numerical techniques, the program manipulates the various constants affecting the transfer function for the particular circuit, searching for minima in the deviation from a straight line. This iterative process halts when a sufficiently good fit to the desired straight line response is found.



One of the many possible configurations of the 4302 multifunction converter shown here allows linearization of an "S" shaped error function. This circuit combines another amplifier with the previous circuit to subtract the generated nonlinear function from the amplified input signal, E1.

Burr Brown applications note AN-128.

MPY634

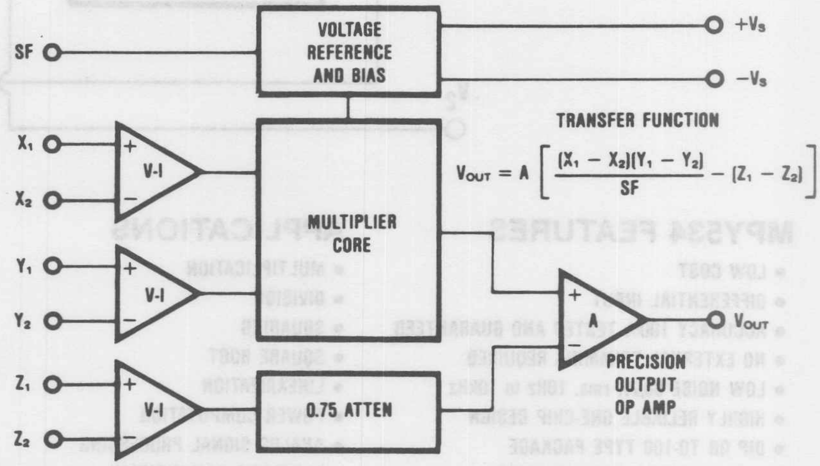
Wide Bandwidth
PRECISION ANALOG MULTIPLIER

FEATURES

- WIDE BANDWIDTH: 10MHz TYP
- ±0.5% MAX 4-QUADRANT ERROR
- INTERNAL WIDE-BANDWIDTH OP AMP
- EASY TO USE
- LOW COST

APPLICATIONS

- PRECISION ANALOG SIGNAL PROCESSING
- MODULATION AND DEMODULATION
- VOLTAGE-CONTROLLED AMPLIFIERS
- VIDEO SIGNAL PROCESSING
- VOLTAGE-CONTROLLED FILTERS AND OSCILLATORS



$$V_{OUT} = A\left[\frac{(X_1 - X_2)(Y_1 - Y_2)}{SF} - (Z_1 - Z_2)\right]$$

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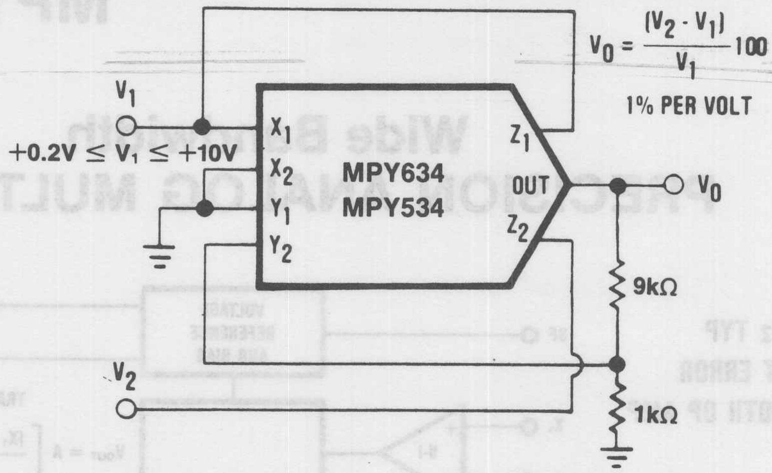
The MPY634 extends the versatility of the analog multiplier function to frequencies up to 10 MHz. Previous analog multipliers have been limited to bandwidths of approximately 1 MHz.

Other "wide bandwidth multipliers" or balanced modulators have had serious limitations. One type commonly used in communications circuitry requires many external components to properly bias its inputs. Furthermore, it nearly always requires extensive trimming circuitry to achieve reasonable balance or carrier rejection. Another wide bandwidth device lacks true four quadrant operation needed for balanced modulation/demodulation applications. Both types require external output amplifiers to complete the circuit function.

PERCENTAGE COMPUTATION



MPY534 FEATURES

- LOW COST
- DIFFERENTIAL INPUT
- ACCURACY 100% TESTED AND GUARANTEED
- NO EXTERNAL TRIMMING REQUIRED
- LOW NOISE 90μV, rms, 10Hz to 10kHz
- HIGHLY RELIABLE ONE-CHIP DESIGN
- DIP OR TO-100 TYPE PACKAGE
- WIDE TEMPERATURE OPERATION

APPLICATIONS

- MULTIPLICATION
- DIVISION
- SQUARING
- SQUARE ROOT
- LINEARIZATION
- POWER COMPUTATION
- ANALOG SIGNAL PROCESSING
- ALGEBRAIC COMPUTATION
- TRUE RMS-TO-DC CONVERSION

TRANSFER FUNCTION

$$V_O = A_{OL}\left[\frac{(X1 - X2)(Y1 - Y2)}{10} + Z2 - Z1\right]$$

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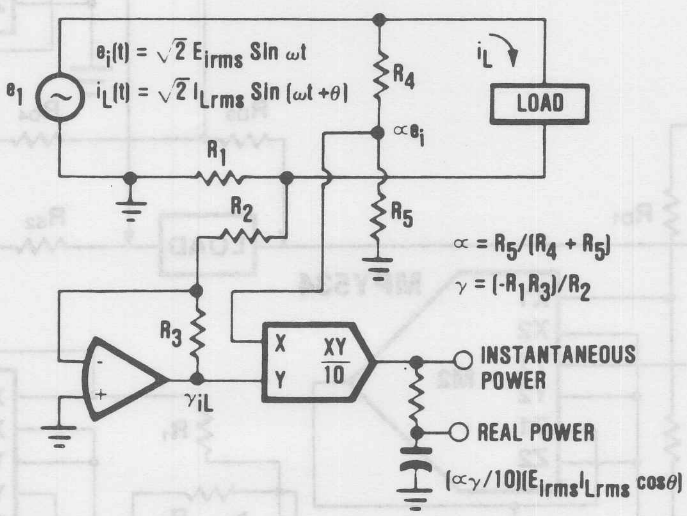
The MPY534 and MPY634 analog multipliers are versatile performers. Their transfer function

$$Vo = Aol * \left[\frac{(X1-X2)*(Y1-Y2)}{10} + Z2 - Z1\right]$$

where the open loop gain of the output stage, Aol, is assumed to be infinite, can be used to create a variety of useful functions. A simple connection using just two external resistors, for instance, provides an output voltage representing the percentage difference between two input quantities.

Many applications circuits, including this one, are easily analyzed by assumptions similar to the ideal op amp. Since any output voltage may be created by an infinite open-loop gain times a vanishingly small input, the quantity inside the brackets may be assumed to be zero. Simple substitution and algebra will then verify the transfer function in the figure. For example in this circuit: X1 = V1, X2 = 0, Y1 = 0, Y2 = Vo/10, Z1 = V1, Z2 = V2. Now substitute these variables into the bracketed portion of the transfer function and set it equal to zero. Then solve for Vout.

SINGLE-PHASE POWER MEASUREMENT



SINGLE-PHASE INSTANTANEOUS AND REAL POWER MEASUREMENT

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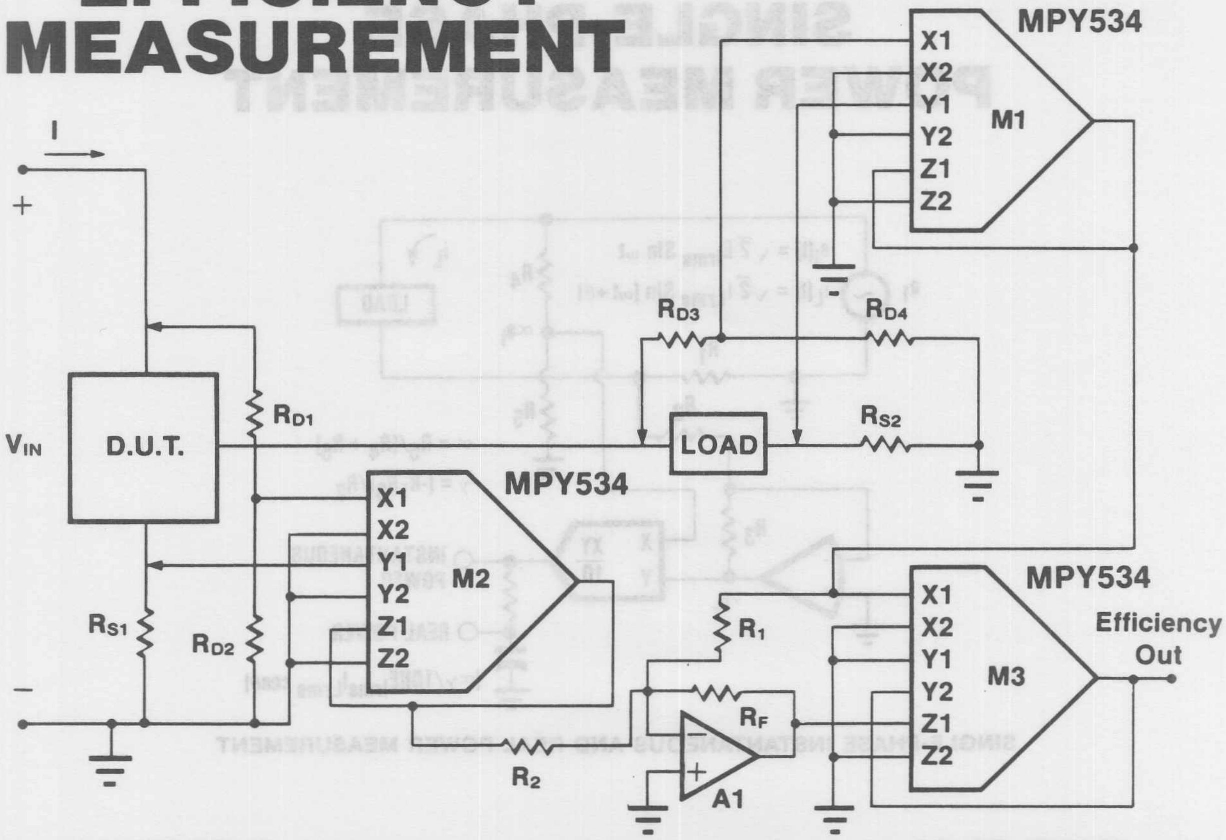
The ability to multiply two voltages representing the instantaneous voltage and current in a load allows simple and direct power measurement. The X input of the MPY634 receives a signal proportional to the load voltage, the Y input receives a signal representing the load current. The multiplier output is then proportional to the instantaneous power delivered to the load.

Although sine wave currents and voltages are assumed in this example, since this measurement technique explicitly calculates with the mathematical definition of power, it is accurate for any source voltage waveform or complex load impedance. Also, the technique is useful over a wide frequency range. This task would be virtually impossible for a processor loaded with any other computational or controlling functions.

EFFICIENCY MEASUREMENT



An expansion of the basics of power measurement allows direct computation of efficiency. This approach makes evaluation of devices such as switching regulators easy. Changes can be made in the Device Under Test and the effect on performance quickly evaluated over a variety of line and load conditions by directly reading efficiency.

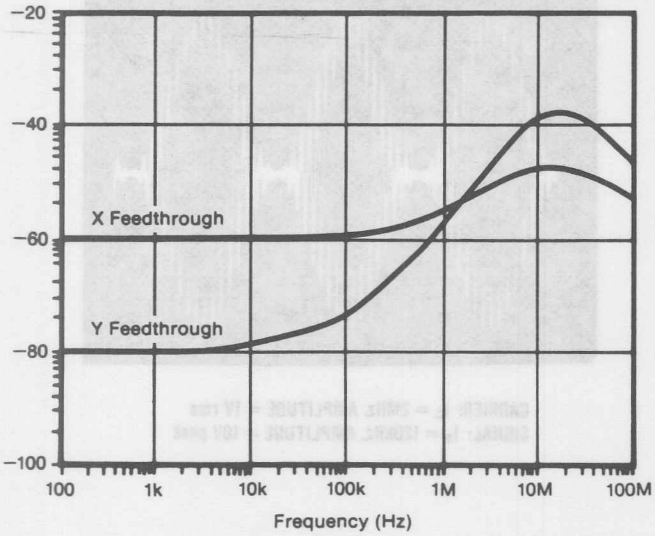
Small value sense resistors are used to sample the current flowing in the load and the ground return leg of the D.U.T. Load power can be computed directly from the V-I product of load current and load voltage in M1.

The other quantity needed for efficiency computation is the input power. Sensing the current in the input line can be problematic, however, since the input voltage to the D.U.T. may be outside the common-mode range of multiplier M2. But it is possible to sense the power dissipated in the D.U.T. itself by multiplying its ground return current and input voltage (divided down).

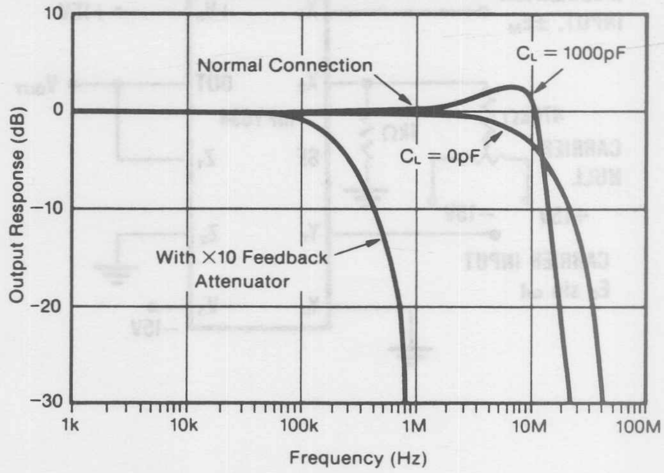
Input power is derived indirectly by summing load power (M1out) and D.U.T. power (M2out) in op amp A1. Efficiency can then be computed in M3 (connected as a divider) by computing the quotient of output power and input power.

THE MPY634 PROVIDES PERFORMANCE NEEDED IN I.F. AND R.F. APPLICATIONS

FEEDTHROUGH VS FREQUENCY



FREQUENCY RESPONSE AS A MULTIPLIER



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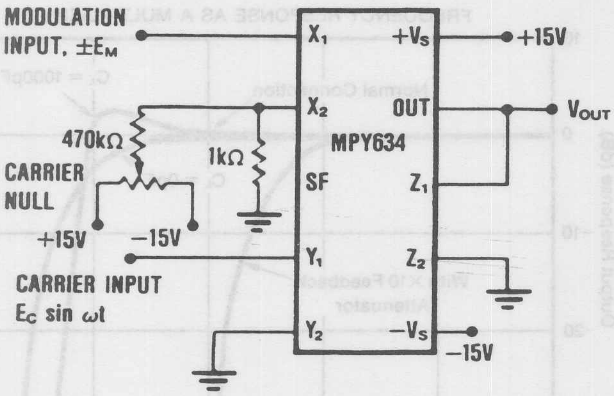
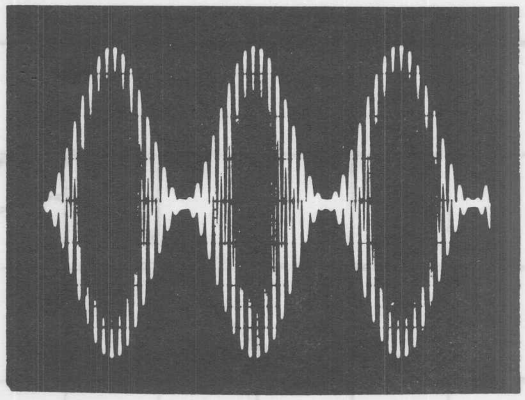
The MPY634 provides specifications required for high frequency designs. Such information as carrier feedthrough verses frequency and bandwidth under varying circumstances provides the RF designer the data required for communications type designs.

A low cost plastic version, the MPY634KP, provides excellent value. It is by far the lowest cost precision analog multiplier available.

MPY634 AS A MODULATOR





CARRIER: f_C = 2MHz, AMPLITUDE = 1V rms
SIGNAL: f_S = 120kHz, AMPLITUDE = 10V peak

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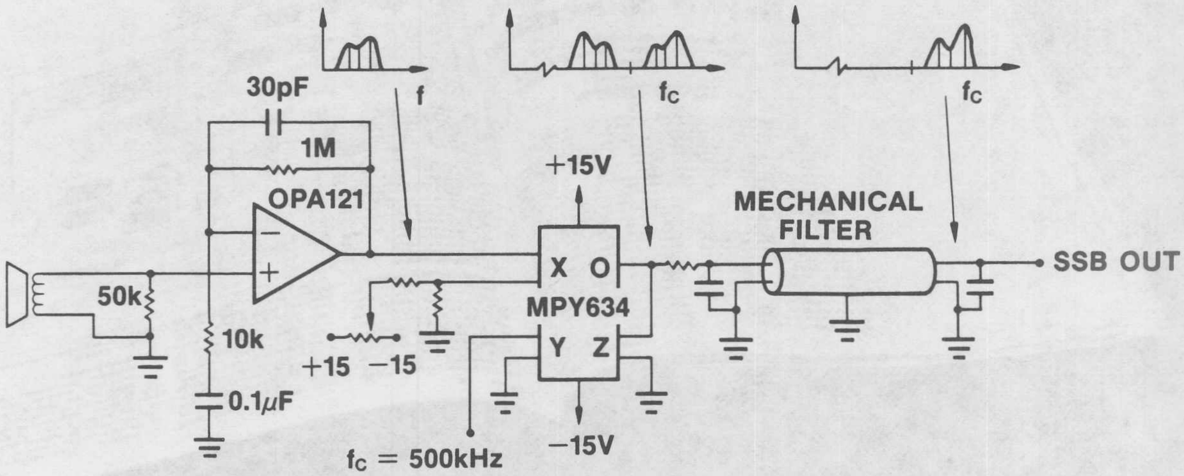
The simplicity of the balanced modulator circuit shown here illustrates the value of the MPY634. No external components are required to produce the double sideband, suppressed carrier waveform shown.

Laser trimming of the offsets of both inputs means that the external trimming network shown on the X2 input can be eliminated in many applications.

SINGLE SIDEBAND GENERATOR



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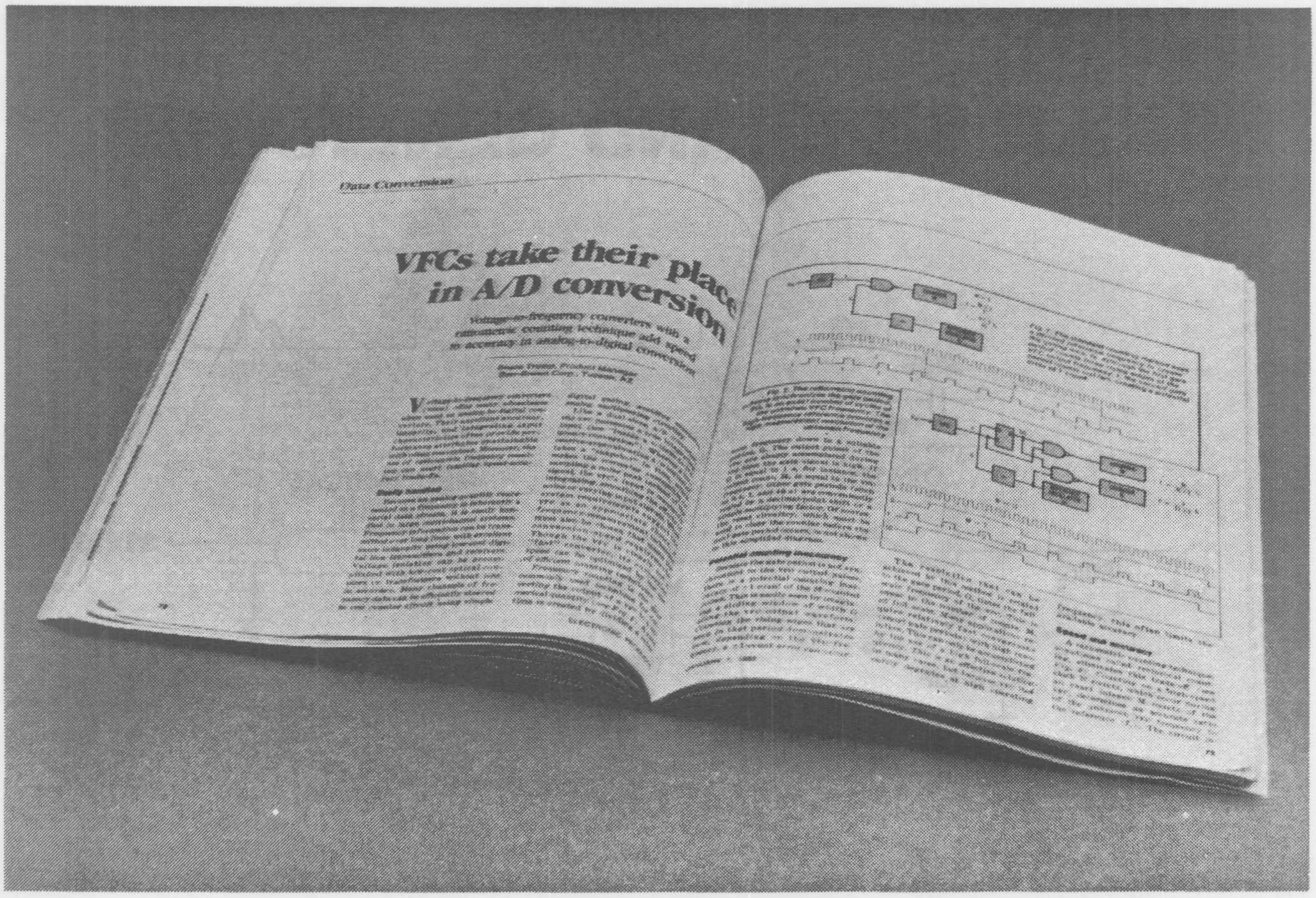
An extension of the basic balanced modulator using the MPY634 adds a mechanical filter on the output. Voice input is amplified and applied to the balanced modulator. The double sideband modulation spectrum shows the input spectrum moved to the carrier frequency. Filtering eliminates one of the two symmetrical sidebands, thus producing single-sideband output.



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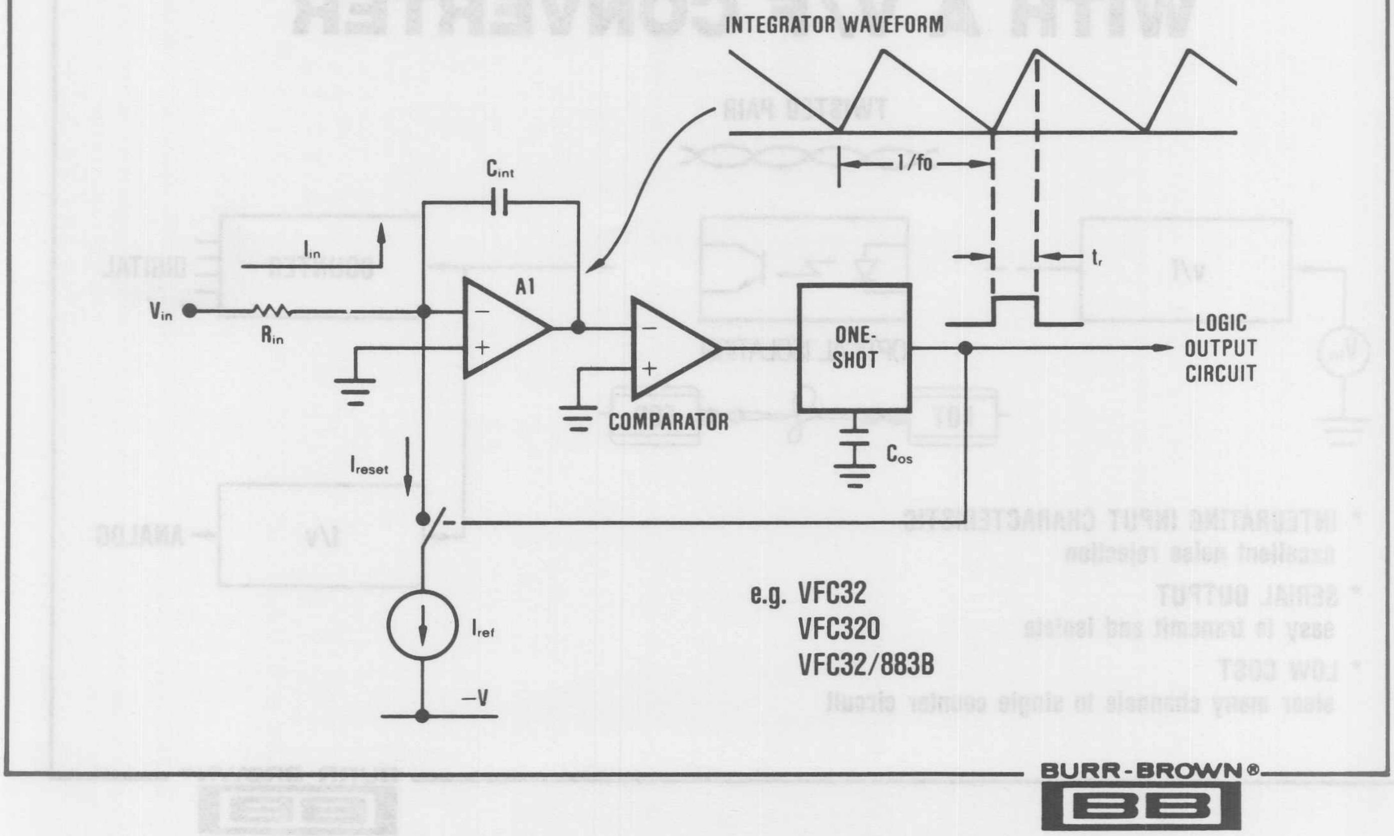
Voltage to frequency conversion is an often overlooked technique for analog to digital conversion which provides unique advantages in many applications.

A BASIC V/F CONVERTER CIRCUIT



The VFC's input voltage develops an input current equal to Vin/Rin which is forced to flow through Cint. This current charges Cint, causing the op amp's output to ramp negatively. When the output of the integrator ramps negatively to the comparator threshold, the one-shot circuit is triggered, connecting the current source, Iref, to the integrator input during the one-shot period. This switched current (constant current for a constant period of time) forces the integrator to ramp positively, crossing the comparator threshold. After the one-shot period ends, the integrator again ramps negatively.

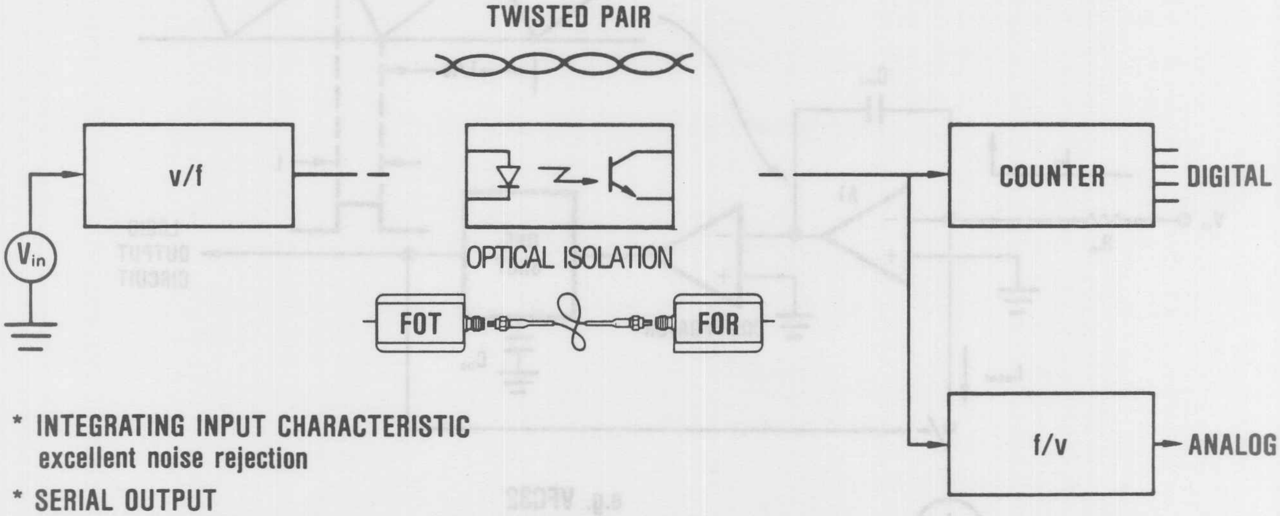
The result is a self-oscillating system which forces the integrator voltage to hover near the comparator threshold. Thus the time-averaged current of the series of reset pulses from the switched current source is forced to balance the input current, Iin. Since the average reset current is proportional to the rate at which the one-shot is triggered, the result is an oscillation frequency proportional to the input voltage.

$$I_{in} = I_{reset}\ (\text{average})$$

$$\frac{V_{in}}{R_{in}} = I_{ref} * f_{out} * T_o$$

Since the input voltage is constantly being integrated, the VFC has excellent noise rejection properties.

A/D CONVERSION WITH A V/F CONVERTER



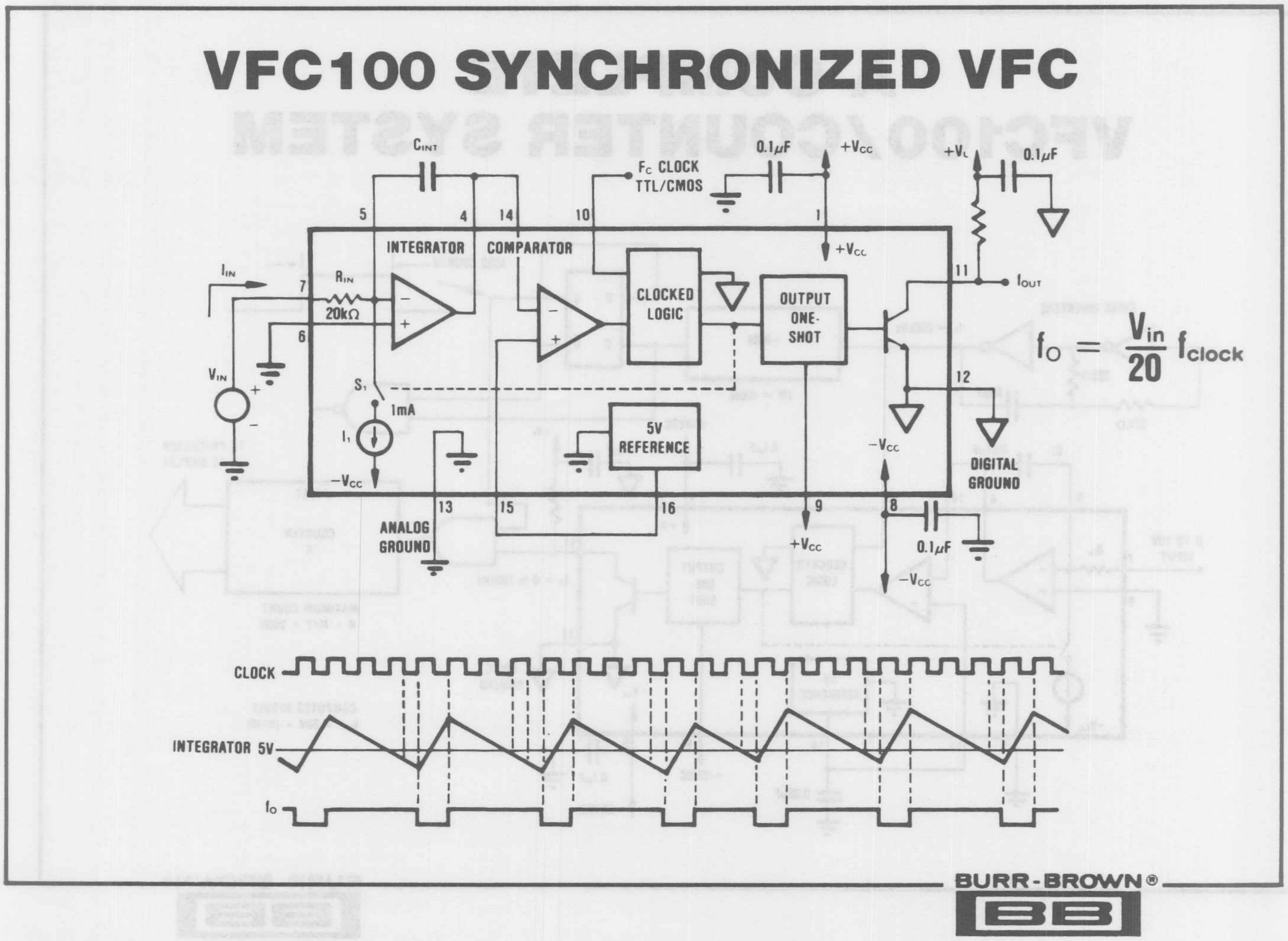
* **INTEGRATING INPUT CHARACTERISTIC**
  excellent noise rejection
* **SERIAL OUTPUT**
  easy to transmit and isolate
* **LOW COST**
  steer many channels to single counter circuit

BURR-BROWN® BB

A/D conversion using v/f converters is an attractive approach in many large system applications. Primary advantages include its integrating input characteristics which affords excellent noise rejection properties.

The serial nature of the VFC's output makes it very easy to provide isolation for safety or noise rejection (ground loop breaking). Frequency data is insensitive to waveform distortion, rise, fall and delay times, greatly easing its transmission requirements.

The VFC provides precision conversion at low cost. Many input circuits can be steered common counter circuitry via digital logic, avoiding expensive analog multiplexing circuitry. Counter/timer peripheral chips are available for virtually all uP families, providing simple and efficient interface to the host computer.



The VFC100, a new breed of VFC, increases accuracy and reduces drift by deriving its one-shot period from an external clock frequency. The one-shot capacitor is eliminated. Its reset current pulses (and output pulses) must align with rising edges of the clock input, causing modulation of the pulse position in the output frequency waveform. Since input and reset currents are held in balance, the output frequency averaged over many cycles is an accurate analog of the input voltage.

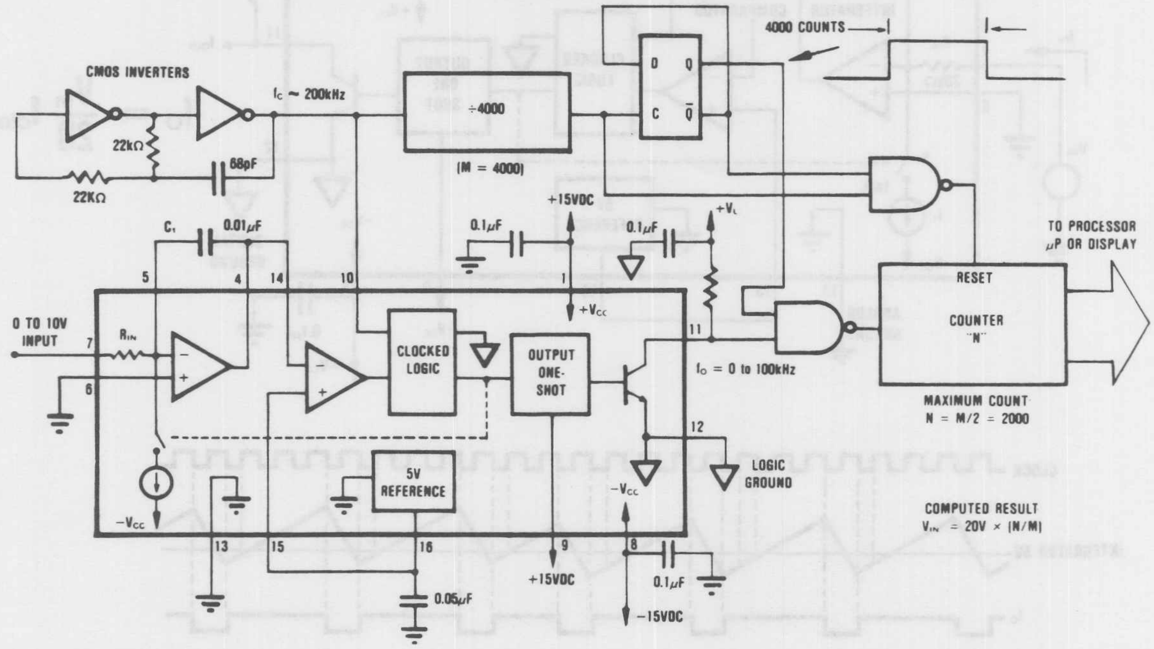
Other features unique to the VFC100 include a reference voltage available for direct offsetting of the input, and an internal laser trimmed input resistor providing an accurate 10 volt full scale value.

The transfer function of the VFC100 is remarkably simple:

fout = (Vin/20 volts) * fclock.

Thus a 10 volt full scale input voltage creates an output frequency of one-half the clock frequency.

A COMPLETE VFC100/COUNTER SYSTEM



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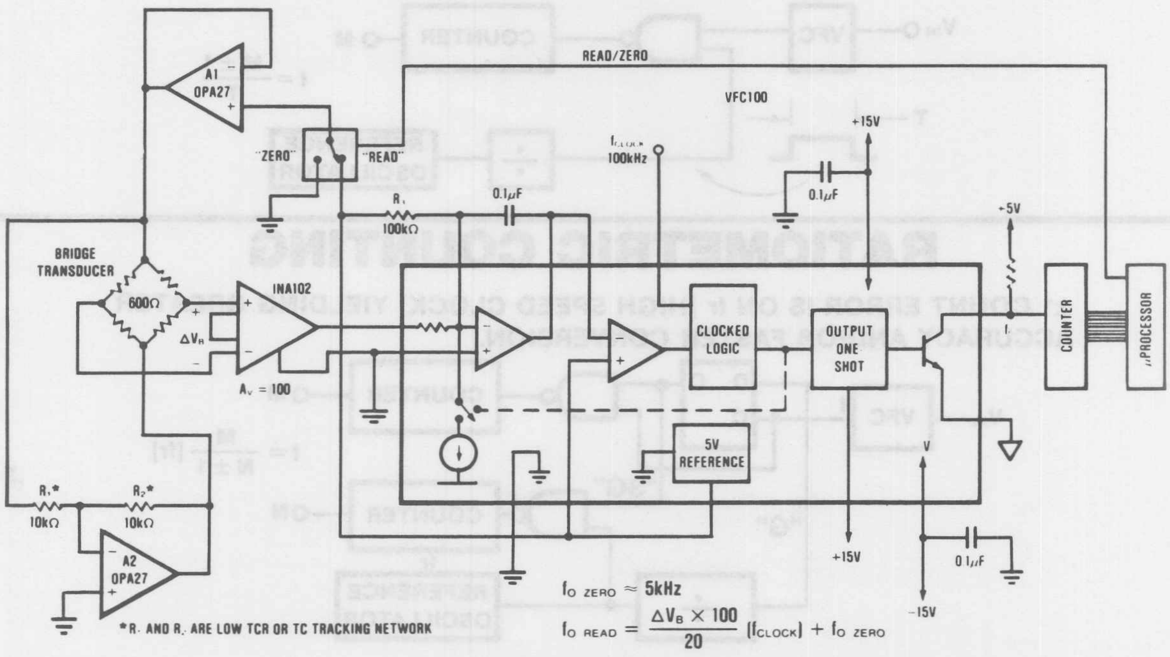
The counter system required to complete conversion to a digital quantity is simplified with the VFC100. By deriving the counting gate period from the same clock controlling the VFC, the exact clock frequency does not affect the counted result. An increase in clock frequency, for instance, creates a higher VFC output frequency, but is also accompanied by a shorter gate period. Thus the same result is achieved.

AUTO-ZERO BRIDGE SYSTEM



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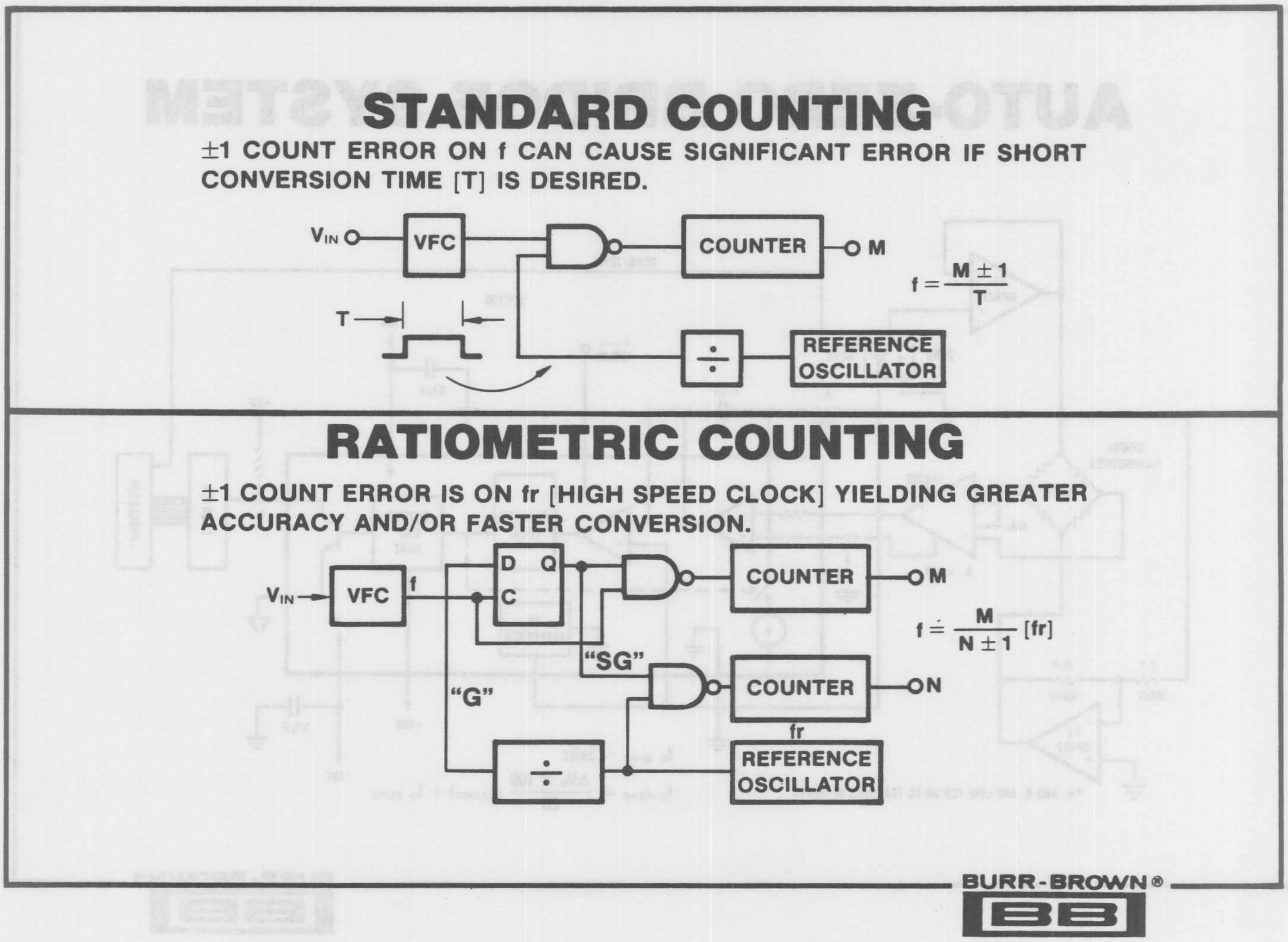
The auto-zero technique shown can achieve outstanding performance in weigh-scale or other sensitive bridge applications. By using the VFC100's internal reference to excite the bridge, extremely low gain drift can be achieved. This technique is viable only with a v-f converter whose transfer function reference voltage is made available to an external pin. Excellent gain drift is maintained by the low drift INA102's internal gain set resistors.

Common-mode errors are virtually eliminated by the balanced excitation technique shown. Since the same common-mode input voltage is seen at the INA102's inputs in both "read" and "zero" mode, the true offset can be measured and stored.

Burr-Brown "Update," XI, No.1.



To complete the A-D conversion, it is necessary to count the VFC output frequency. The standard frequency counting approach (upper figure) simply totals the number of VFC pulses which occur during a fixed gate period. The gate period is generated by counting a fixed number of cycles of a reference clock frequency. This counting method is subject to an error of +/- one count since the gate period is not correlated with VFC output pulses.

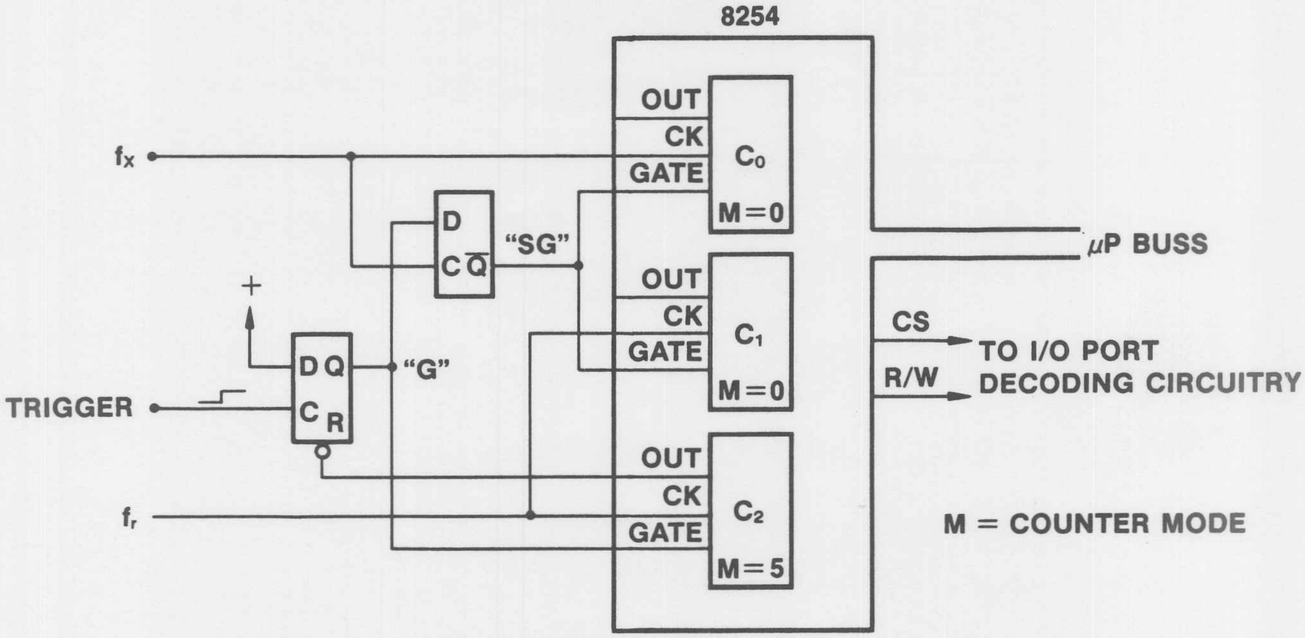
The ratiometric counting technique (lower figure) synchronizes a new gate period, SG, to an exact number of counts of the VFC. This synchronized gate is used to simultaneously count high frequency clock pulses, N, and the exact number of VFC pulses, M. Since the reference clock is uncorrelated to the synchronized gate, its count, N, has a potential one count inaccuracy. With the one count error occurring on a large number, greater counting resolution can be obtained in short conversion times.

This technique allows the VFC to be run at a low frequency where its linearity it optimum.

"VFCs take their place in A/D conversion," Electronic Products, January 1, 1985.

"V-F converters offer useful options in A/D conversion" Burr-Brown application note AN-130.

RATIOMETRIC COUNTER DETAILS



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Ratiometric counting is easy to implement using one of the many counter-timer peripheral components available for most major microprocessor families. The type 8254 (Intel) interfaces easily with the Z-80, 8086 and the IBM buss structure. Three independent counters in the 8254 (C0, C1 and C2) are used to make one complete counter system. C2 counts the reference frequency to create the main gate period. Counter C0 counts VFC pulses, while C1 simultaneously counts high frequency reference clock pulses.

The "D" flip-flop synchronizes the gate signal "SG" with an exact number of cycles of the unknown frequency input, fx. On completion of the count, data describing the ending counts of C0 and C1 are read by the microprocessor. The ratio C0/C1 times the reference frequency fr is computed in the processor to achieve the final result.

For multiple channel systems, the function of C2 need not be repeated. Other channels could be counted using just two of the three counters of each additional 8254 peripheral component.

BURR-BROWN DATA CONVERSION PRODUCTS

SPECIFICATIONS AND APPLICATIONS

BURR-BROWN®

BIPOLAR PROCESS OPTIMIZED FOR DATA CONVERTERS

- **20 VOLT THIN-EPITAXIAL LAYER**
  HIGHER SPEED, SMALLER SIZE
- **THIN-FILM COMPATIBLE Ni Cr RESISTORS**
  HIGHER ACCURACY, GREATER STABILITY
- **SUBSURFACE ZENER DIODE**
  STABLE VOLTAGE REFERENCES

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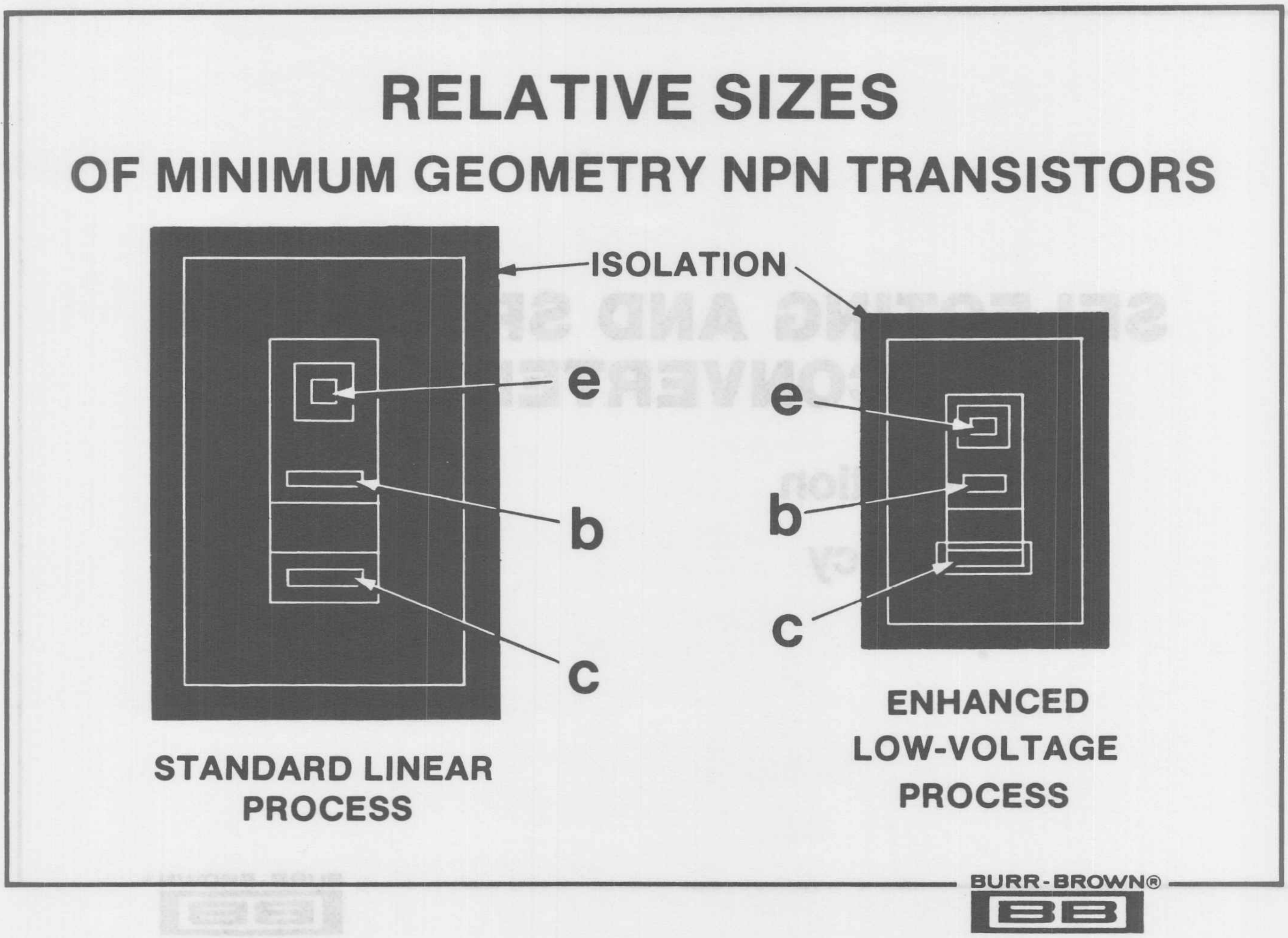
102 Burr-Brown has developed a special bipolar process optimized for data converters. This was possible because most data converter designs are not required to operate with the high common mode voltages commonly associated with operational amplifiers and instrumentation amplifiers.

Burr-Brown's thin-film resistors offer high accuracy and excellent stability. We have recently introduced a 15-bit linear 16-bit resolution D/A converter made possible by improvements over the years.

The addition of a stable sub-surface zener diode for the heart of the converter reference allows converters to be completely self-contained. This permits optimum specifications, maximum ease of use without an abundance of external components, and minimum occupied space per function. All this results in lowest overall installed cost.



103 Most converter manufacturers of bipolar monolithic converters used the wafer fabrication process inherited from operational amplifiers. In order to complete the converter function, they all needed to develop a low noise on-chip reference.

Since die sizes tended to get large for converters using these op amp processes, Burr-Brown developed a low-voltage process for its bipolar converter designs. This resulted in a considerable reduction in die size for 12-bit and up resolution converters compared to those built on the 40-volt op amp process.

Due to the thinner epitaxial layer in Burr-Brown's low-voltage process, the lateral or "side-diffusion" of the isolation walls is much less. This allows closer device spacing. The actual device diffusions are also shallower. All this results in smaller, higher speed devices.

SELECTING AND SPECIFYING CONVERTERS

- Resolution
- Accuracy
- Speed

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104 For years A/D and converters have had a data acquisition look about their specifications. They were essentially DC specifications. The advent of digital signal processing applications has brought about a change in the way converters are being specified. These applications range from consumer products such as the compact disc; laboratory instruments such as waveform analyzers of all types; to radar and sonar designs that require that the A/D converter almost be connected directly to the antenna or the transducer.

Today A/D and D/A converter specifications are becoming more and more specialized to the application. An example, particularly for Burr-Brown over the past 5 years, is the specification of PCM audio A/D and D/A converters. These are specified for total harmonic distortion at two or three signal levels. The other DC specs we are all familiar with are very few or very loose or don't exist at all!

CONVERTER SELECTION

General Considerations

- **External Parts**
  - -Potentiometers (for calibration)
  - -Op amp, buffer (one or more)
  - -Reference voltage
  - -Clock (crystal)
  - -Resistors, capacitors
- **Package Size**
  - -Including external parts

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105 But first, let's consider the circuit environment of the converter.

External parts are often required for converter operation. Potentiometers for GAIN and OFFSET adjustment are the most common requirement because initial GAIN and OFFSET specs are typically 0.1% to 0.3% of Full Scale Range.

An op amp may be required to buffer the input to an A/D or to provide an I-to-V converter for the output of a D/A converter.

A reference voltage, a clock (perhaps a crystal) and various resistors and capacitors may be required. Some may require resistors to be matched in temperature coefficient.

These all add power dissipation and additional cost over the converter component itself.

Package size -- the total package size including the external components should be considered.

CONVERTER SELECTION

General Considerations

- **Noise Environment**
  A more complete converter may be less susceptible to noise.
- **Power Supplies**
  -Switching type
  -Linear type
  -Batteries

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106 A complete converter may be less susceptible to externally generated noise because of the smaller cross-sectional area presented to the interference fields.

Of course, linear type power supplies are best for powering high resolution converters. Switchers, with their high frequency energy content are difficult to shield and filter.

When using batteries one must be sure the output impedance is appropriately low (to prevent poor regulation effects) and that the range of power supply operation of the converter is wide enough to allow for discharge of the battery.

WHAT ACCURACY IS REQUIRED?

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RESOLUTION ≠ ACCURACY

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108 Resolution and accuracy are not the same thing although the jargon that is sometimes use in informal conversation, and perhaps advertising, to describe converters sometimes substitutes one for the other.

Because of the way converter specifications are organized, RESOLUTION does not imply ACCURACY nor does ACCURACY imply RESOLUTION.

ACCURACY AND THE NUMBER OF BITS

Number of Bits (n)	Number of Increments 2^n	Increments As a % of FSR	1/2 Increment (1/2 LSB)
16	65,536	.0015%	.00075%
14	16,384	.006%	.003%
12	4,096	.024%	.012%

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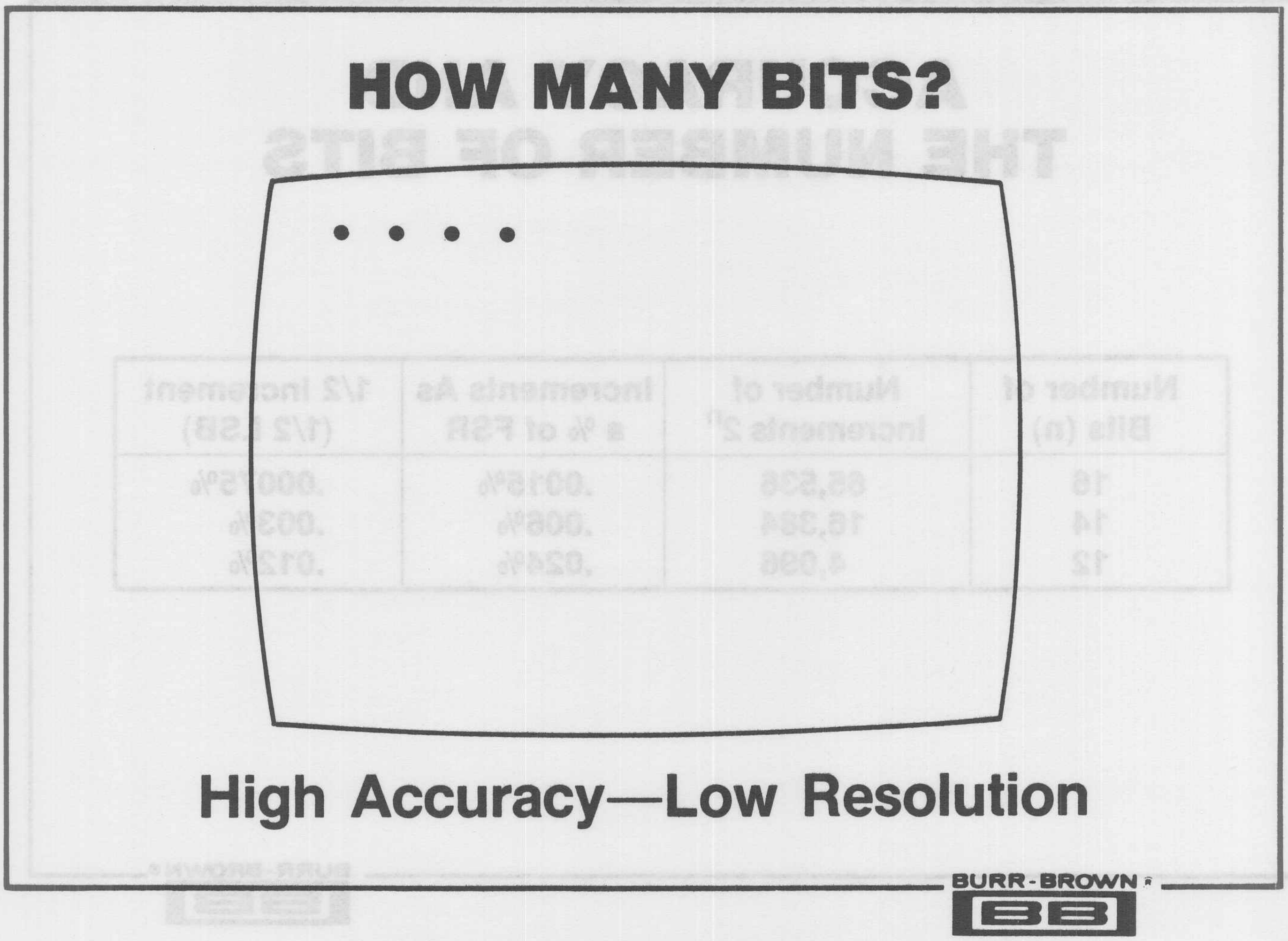
109 Resolution is the full scale range of a converter divided by the number of quanta or steps the converter is capable of resolving. This number is 2 raised to the nth power where n is the number if binary digits (bits for short) of the converter. Sometimes we say a converter has 12-bits of resolution. This is an imprecise description of the resolution of the converter, but it is short and convenient.

Accuracy describes the relationship of the transfer characteristics of a real converter to the transfer characteristics of an ideal or perfect converter.

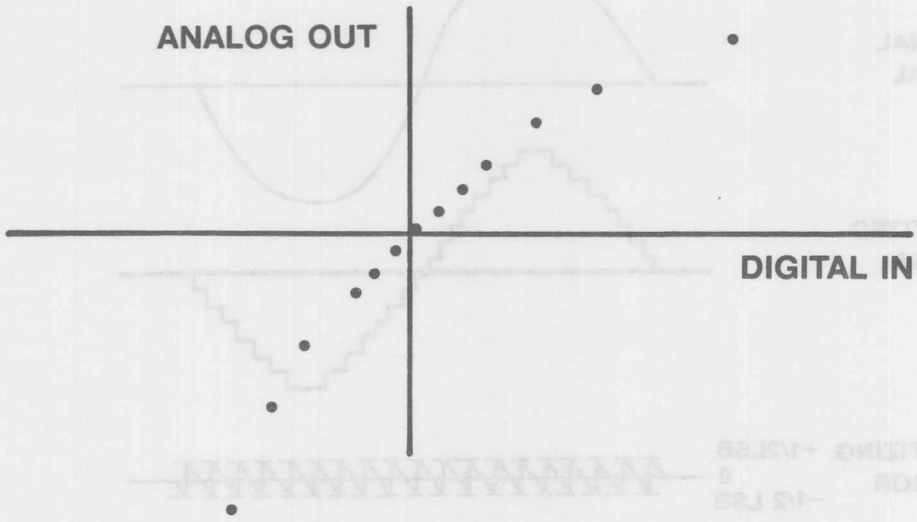
The table above shows the relationship of various terms used to describe converters. FSR = Full Scale Range; LSB = Least Significant Bit.



110 Generally one specifies a converter capable of resolving a signal into quanta that are perhaps 5 to 10 times smaller than the target resolution of the system being designed. This assumes that the noise levels on the signal are also lower than the target resolution. This choice is especially true if the application is a pure measurement - take one measurement and store or read the result such as a weighing scale application would require.

There are applications where resolution and accuracy (or integral linearity do not go hand in hand. This slide shows a situation where low resolution but high accuracy is required of a D/A converter. One may wish to position an electron beam at 256 locations but may wish each position to be to within +-0.012% of full scale. Here the application requires an 8-bit resolution D/A converter but with a relative accuracy normally specified for 12-bit converters.

HOW MANY BITS?



High Resolution—High Non-Linearity

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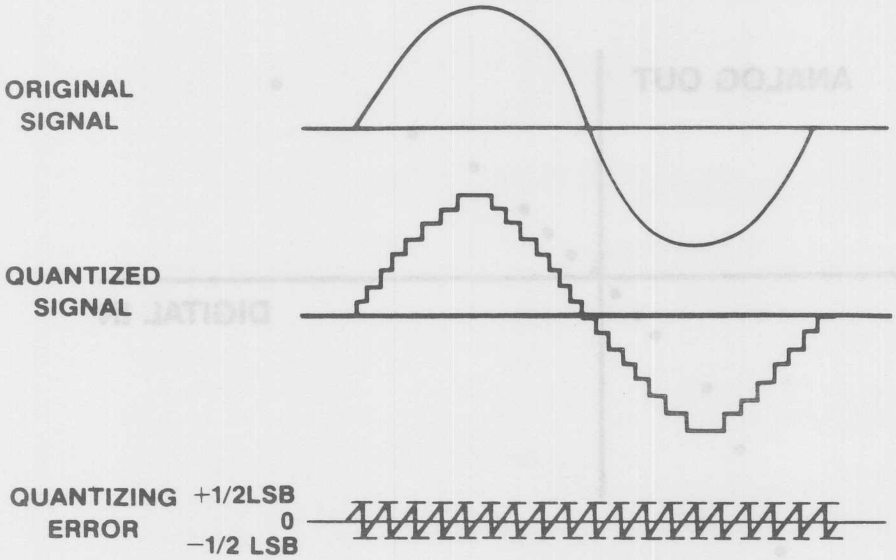
111 On the other hand, a motor controller application may require small steps of control of the velocity especially around zero velocity. But the linearity error tolerated may be less than the resolution would suggest. Thus the D/A converter may be specified to have high resolution, say 16-bits, but with a linearity error of +-0.02% of full scale, a linearity error one would expect of an 11-bit converter. Of course, in this application, the converter must be MONOTONIC for its codes near zero or the controller would forever hunt for the right velocity.

HOW MANY "BITS" ARE REQUIRED?



$$DR = \frac{\text{MAXIMUM SIGNAL}}{\text{QUANTIZING NOISE}} = [6 \times \text{NUMBER OF BITS} + 1.8]\ \text{dB}$$
$$= 49.8\text{dB [8 BITS]},\ 73.8\text{dB [12 BITS]},\ 97.8\text{dB [16 BITS]}$$

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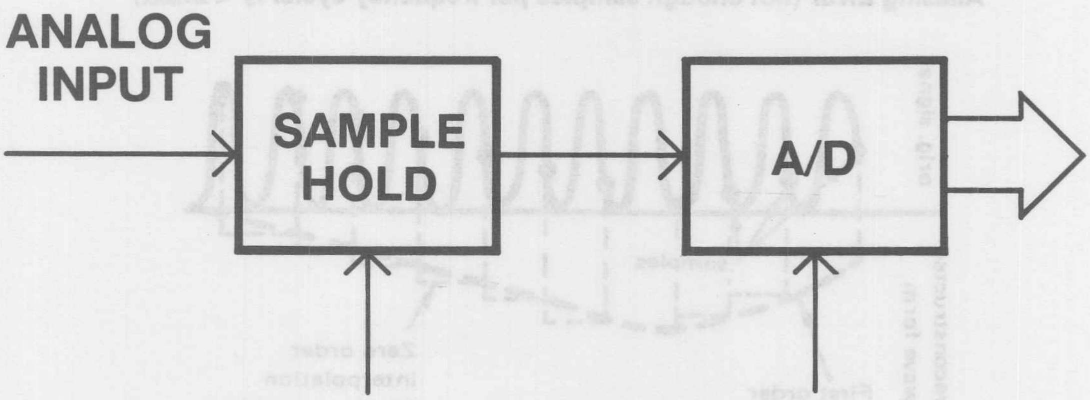
112 Other applications express the resolution need in terms of dynamic range. These applications might be waveform analysis applications followed by some digital processing such as in geophysical measurements, or closer to home, digital audio tape recorders.

Dynamic range requirements are converted to A/D converter binary digits (bits) as shown above. Of course, quantizing noise of any given n-bit converter sets a limit on the usable dynamic range. Other system electrical noise will add quantizing noise and 1 or 2 least significant bits may be useless unless some digital signal processing can remove the effect of the unwanted noise.

WHAT SAMPLING RATE IS REQUIRED?



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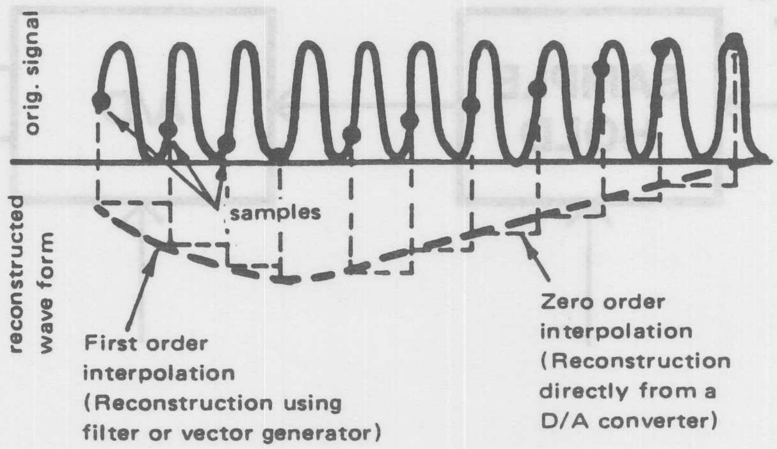
113 Sample-holds are used to increase a data acquisition system's throughput rate. A/D converters, except integrating A/D converters, accurately sample the input signal only if the input signal is constant during the conversion time. A sample-hold provides this constant value.

SYSTEM SAMPLING RATE

Aliasing Error (not enough samples per frequency cycle: $f_S < 2f_{MAX}$)



Aliasing Error vs Sampling Rate

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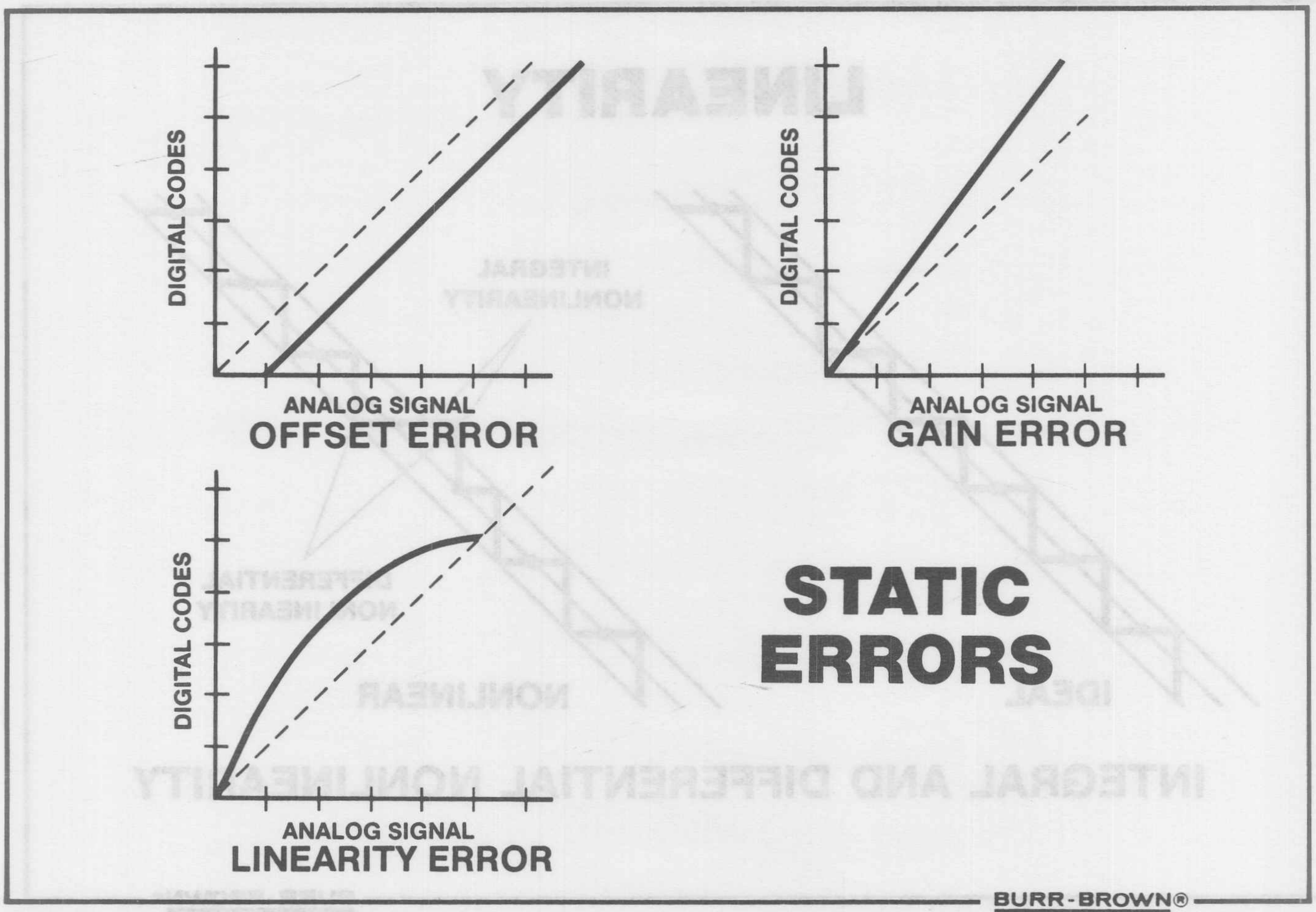
114 The selection of a system sampling rate is bounded by the Nyquist sampling theorem which defines the minimum sampling rate for a bandlimited signal. The minimum rate is required to avoid aliasing errors.

Aliasing error is the error which can occur if this relationship is not observed and results in significant waveform distortion. The result of aliasing can also be thought of in terms of a "beat frequency" resulting from mixing the input signal with the sampling frequency (local oscillator).

The two samples per cycle limitation is nearly approached in earlier compact disc players where a sampling rate of 44kHz is used to sample a 20kHz bandwidth audio signal or the new Digital Audio Tape 48kHz to sample a 22kHz bandwidth audio signal.

For many industrial applications, a sampling rate of much greater than 2X is required because ACCURACY of the measurement is important or the aliaising filter requirements are too severe for a practical implementation.

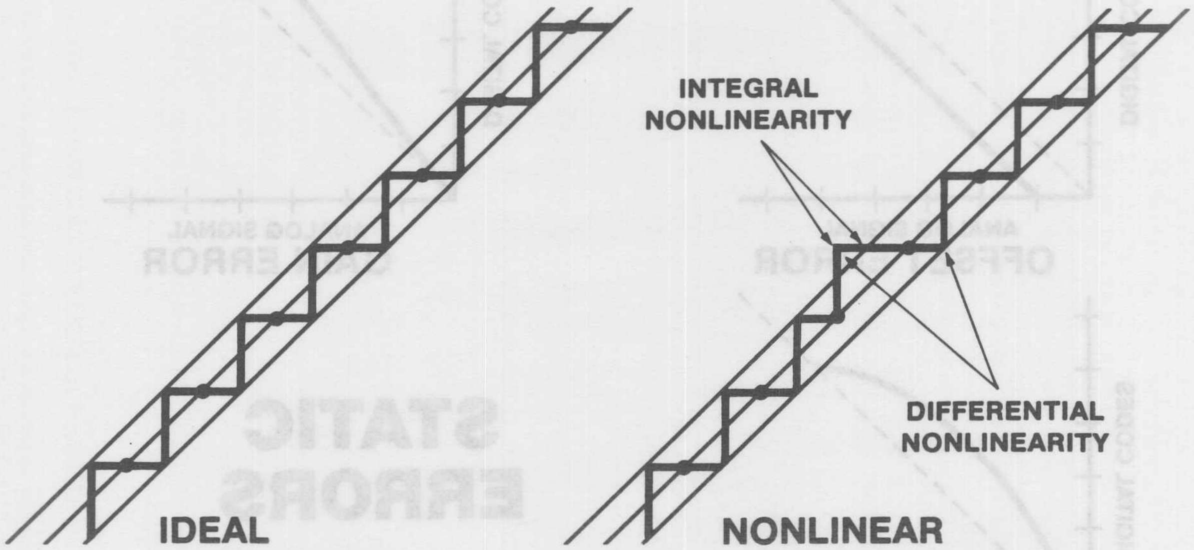


115 Static errors are errors which exist without regard to speed or dynamic conditions. That is the converters are tested with low frequency signals in the case of A/D converters, and after all transients have settled in the case of D/A converters.

The error specifications shown here are in all texts and references on converters.

A spec worth mentioning, because it is changing its form on many converter specification sheets, is the OFFSET spec when it is applied to bipolar configured converters (converters with + and - analog ranges). In the past BIPOLAR OFFSET has been specified and tested at minus full scale. However BIPOLAR ZERO, the performance at zero volts input (A/D converters) or output (D/A converters), is of more interest in most applications. Remember the motor velocity control application. You will probably see a BIPOLAR ZERO specification more often than BIPOLAR OFFSET in the future. UNIPOLAR OFFSET does not change because it already is defined at zero volts.

LINEARITY



INTEGRAL AND DIFFERENTIAL NONLINEARITY

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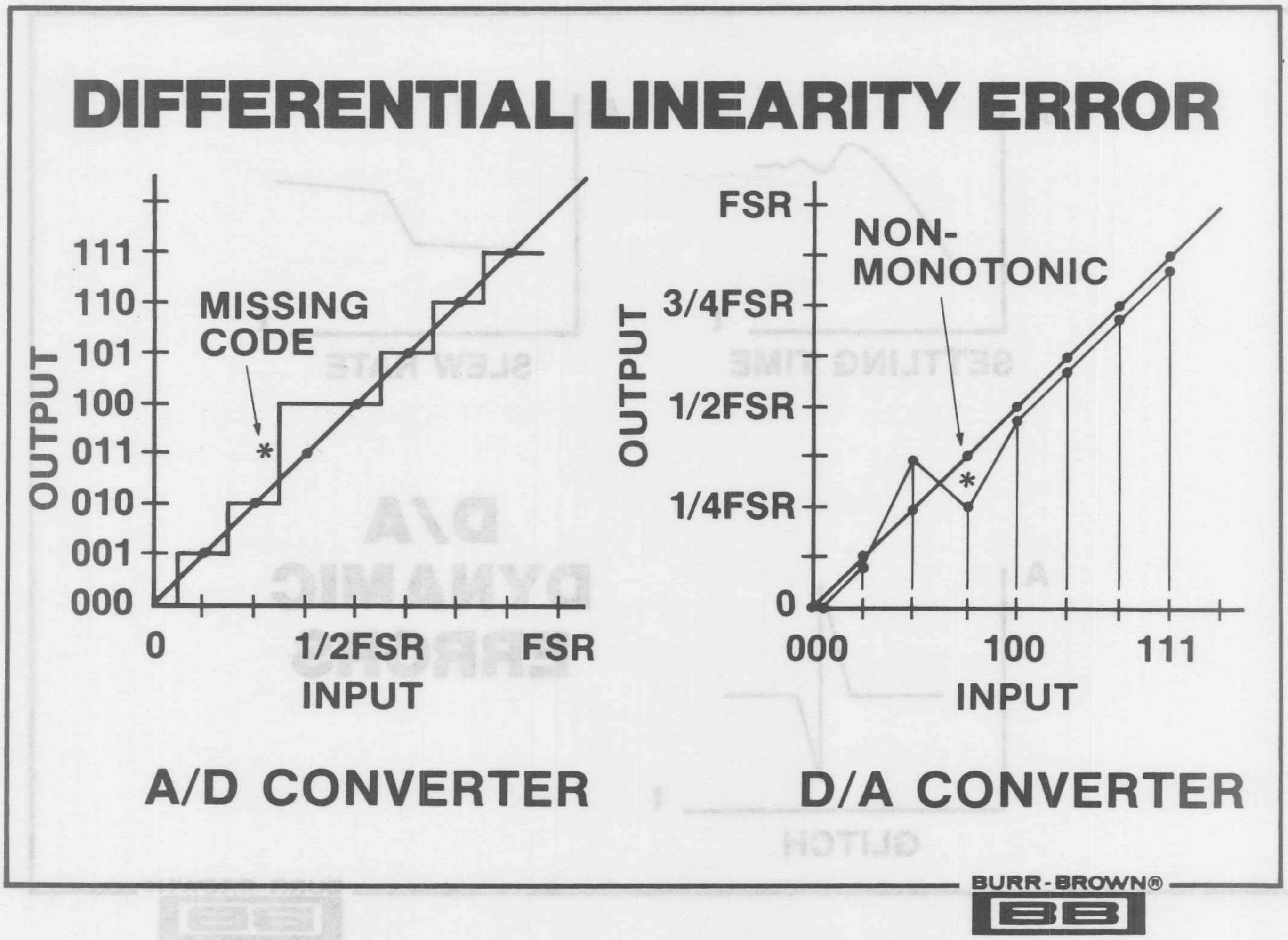
116 There are two linearity error specifications for converters INTEGRAL LINEARITY ERROR (often called just LINEARITY ERROR or NON-LINEARITY, sometimes RELATIVE ACCURACY) and DIFFERENTIAL LINEARITY ERROR.

INTEGRAL LINEARITY ERROR is the maximum deviation, anywhere along the transfer characteristic of the converter, from a straight line (usually drawn between the end points). This is the definition used by most converter manufacturers. It is also known as RELATIVE ACCURACY and, in industrial measurement and control circles, as TERMINAL LINEARITY. It is a conservative definition compared to the "best-fit straight line" definition.

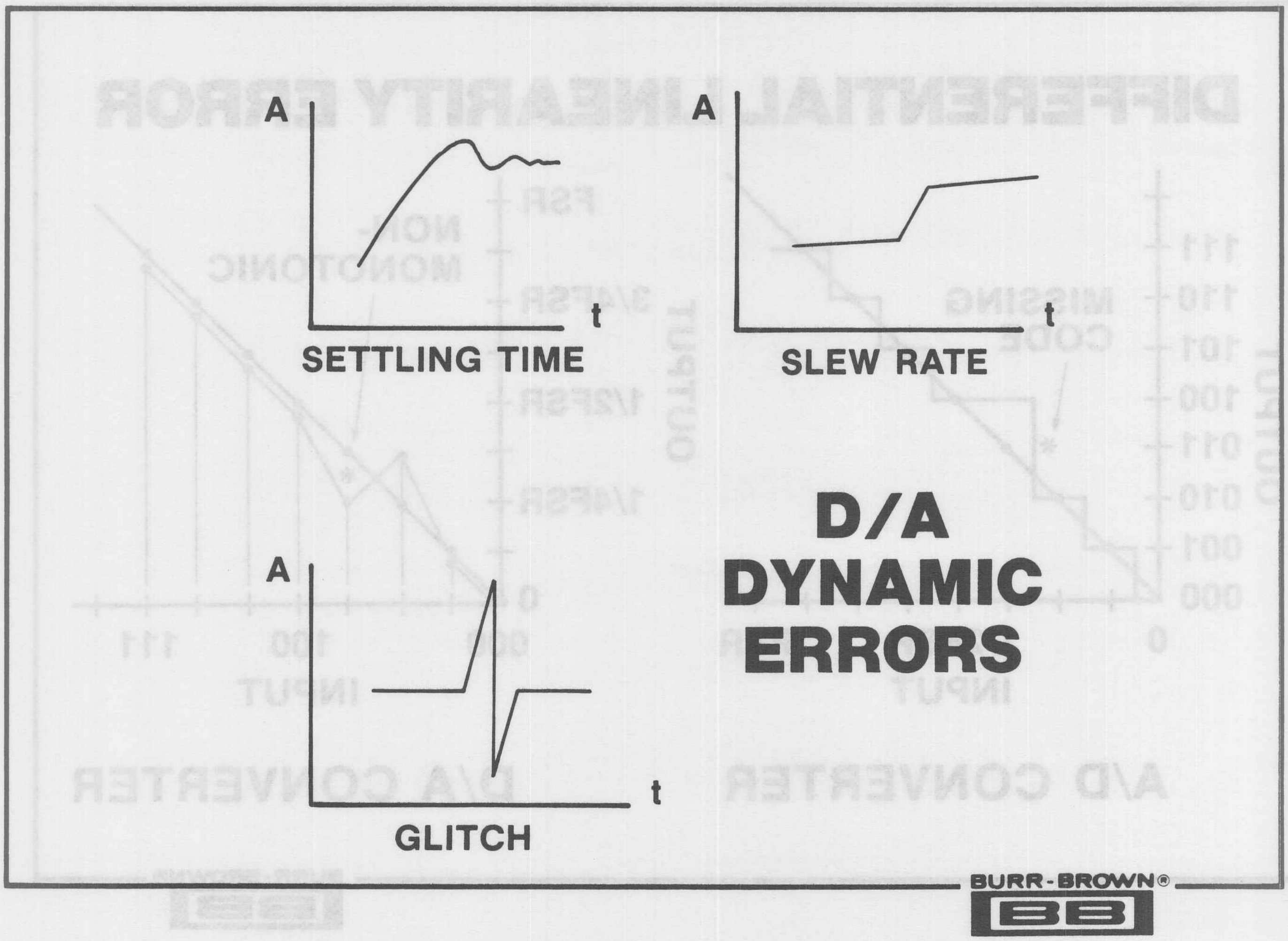
DIFFERENTIAL LINEARITY ERROR is an error in the difference of the analog values associated with two adjacent codes. Ideally this value is one Least Significant Bit (LSB). The deviation from one LSB, between two steps anywhere on the transfer characteristic of the converter is a DIFFERENTIAL LINEARITY error.



117 For D/A converters, a DIFFERENTIAL LINEARITY ERROR of greater than -1 LSB will result in non-monotonic behavior. That is the transfer characteristic doubles back on itself. This is very undesirable in many applications. Remember the motor controller. Note that an error greater than +1 LSB will not result in non-monotonic behavior but an error of greater than -1 LSB will. MONOTONICITY is a useful spec for D/A converters especially if it is guaranteed over temperature.

An A/D converter with a DIFFERENTIAL LINEARITY ERROR of greater than 1 LSB will undoubtedly have missing codes. This may not be too serious in many applications except perhaps when your A/D is making absolute measurements such as in a weighing scale or a digital voltmeter.

MONOTONICITY is not a term often applied to A/D converters. MISSING CODES is the useful specification for A/D converters especially if NO MISSING CODES is guaranteed over temperature. DIFFERENTIAL LINEARITY is a useful for A/D converters and may be a key spec in some applications.

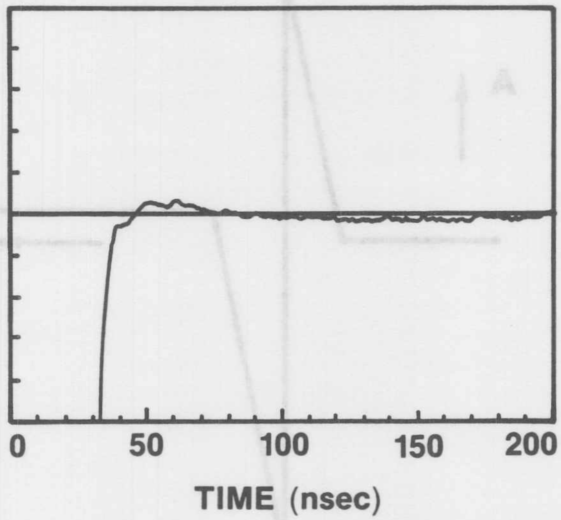


118 Dynamic errors in D/A converters are becoming more important specifications especially as more instruments and test systems use digital techniques to generate test signals and AC waveforms.

These dynamic errors, if they are large enough, can cause unwanted energy in the passband of interest.

On the other hand, D/A's used for beam positioning are required to have low glitch and fast settling time characteristics, as well as excellent differential linearity in order to present a clean display.

SETTLING TIME



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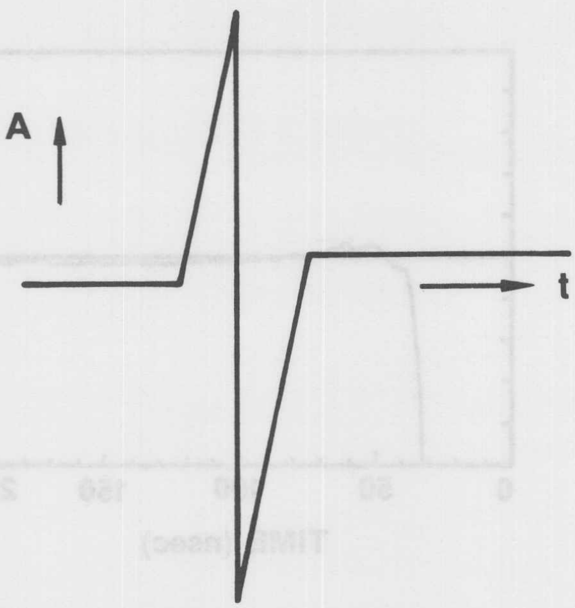
119 SETTLING TIME is a D/A converter spec familiar to engineers ever since D/A's have existed. Shown here is the settling waveform of a very high speed D/A converter. A settling time amplitude window is specified. The time at which the amplitude of the output enters the window and stays within the window is called the SETTLING TIME. SETTLING TIME includes the slewing time.

GLITCH



**GLITCH ENERGY = NET AREA
IN PICOVOLT-SEC (pVs)**

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120 The so-called glitch at the output of a D/A converter is the result of uneven switching times (digital skew) in the digital bus and even in the circuitry of the D/A converter. A transient of voltage (or current) appears at the output of the converter during and just after the data changes state. This spike is its greatest whenever the Most Significant Bit (MSB) switches on or off.

This transient is highly undesirable in many applications such as CRT display driving applications or in waveform generators that use digital synthesis.

The specification for GLITCH is the net area, that is, the mathematical difference of the positive spike area and the negative spike area under the waveform. The net area is expressed in picovolt-seconds (pV-s).

Many D/A converters have following circuits of lower bandwidth connected to their output. In these cases the net area spec is appropriate for estimating the effect of the glitch at the output of the low-bandwidth circuit.

Applications that are sensitive to the magnitude of the spike may require a magnitude spec.

A/D APPLICATIONS

Application	DVM	Signal Processing	Audio
Relevant Specification (In order of importance) 1.	Accuracy	Accuracy	Speed
2.	Drift	Resolution	Resolution
3.	Resolution	Speed	Accuracy
4.	Speed	Drift	Drift
Additional Performance Requirements		Spectral Purity	Spectral Purity

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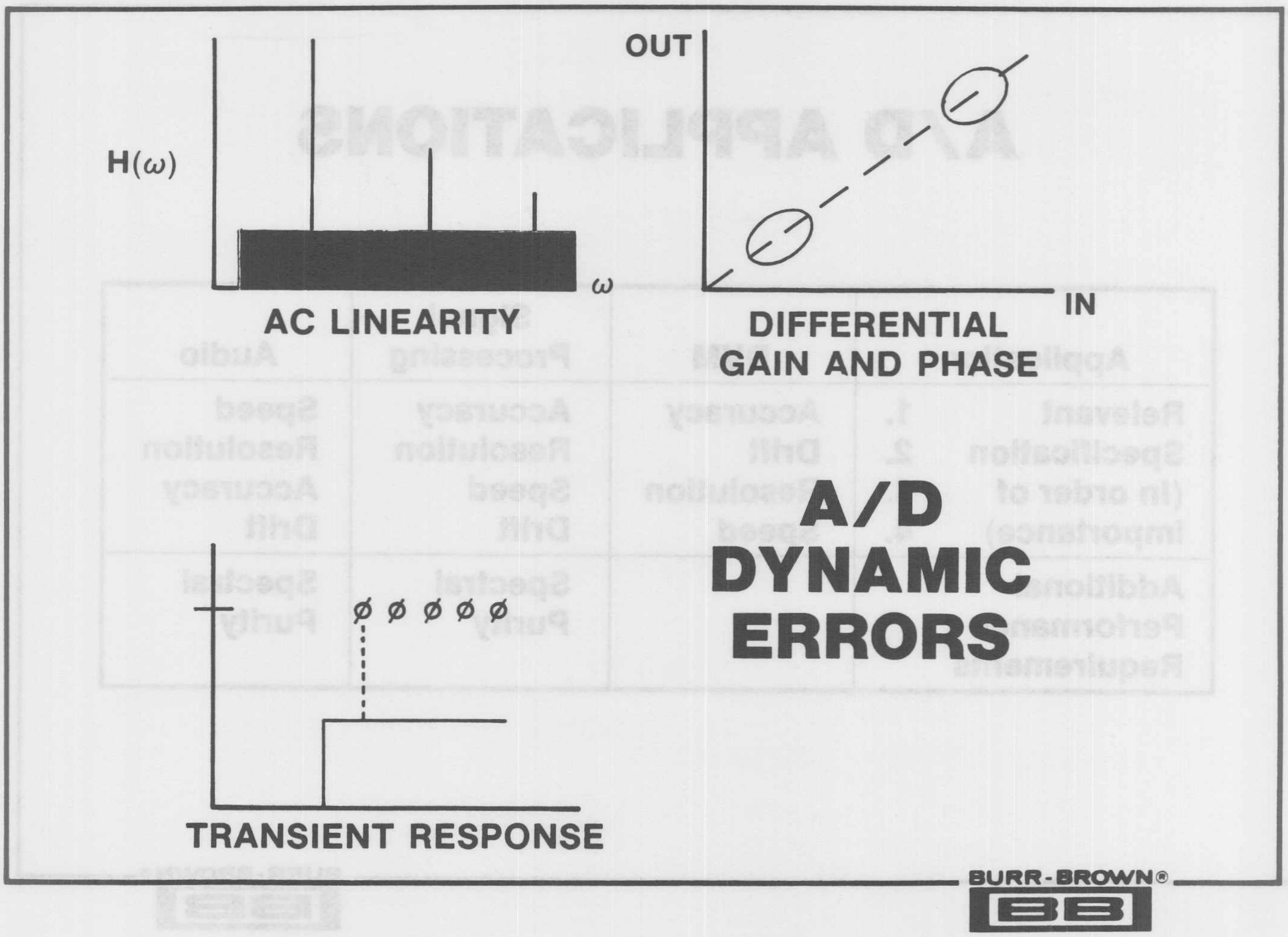
121 This slide illustrates the different application points of view possible when applying A/D converters. Applications that may require DYNAMIC ERROR specs will be discussed in this section.

The DVM is an example of a "static" application, while the digital audio application requires good dynamic performance.

More new converters are being characterized for Harmonic Distortion, Intermodulation Distortion, Spurious Responses, and Signal-to-Noise.

Spectral purity has not been specified much in the past. But now these AC-type specifications are showing up more and more on data sheets especially for relatively high-speed converters. Applications requiring spectral purity are good candidates for converters whose accuracy specifications are not as high as their resolutions would suggest.

Incidentally these AC specs are more useful to the user if the sample-hold is included in the specification.



122 Many new specs are beginning to show up on data sheets especially for A/D converters used in DSP applications. These specs describe the dynamic performance of the converter and they are frequently more important than traditional DC linearity or accuracy specs.

AC linearity---

Transient Response--

Signal-to-noise ratio--

Noise Power Ratio--

Differential Gain and Phase--

AC LINEARITY ERROR

- Harmonics of Input Frequency
- Intermodulation Products

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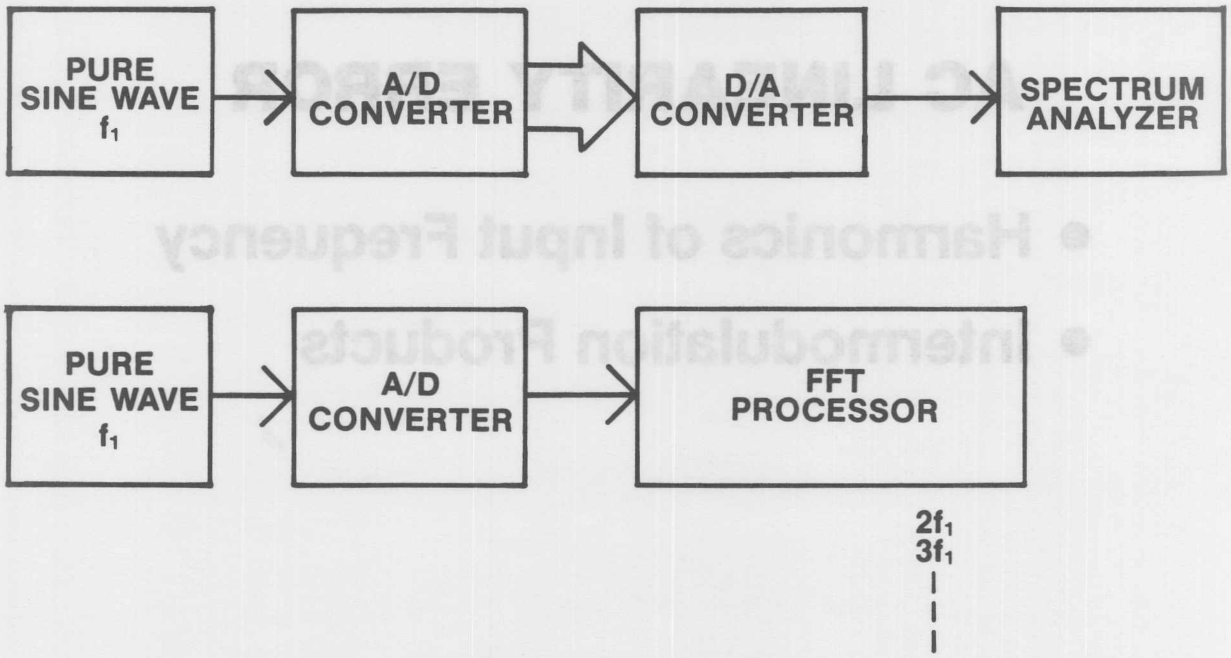
123 AC-linearity error refers to the fact that harmonics of the input to the converter are generated in the converter and appear in the output data word stream. Intermodulation products of multiple frequency inputs are also generated.

HARMONIC DISTORTION



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124 There are really no surprises about the way HARMONIC DISTORTION must be measured. However there are some considerations.

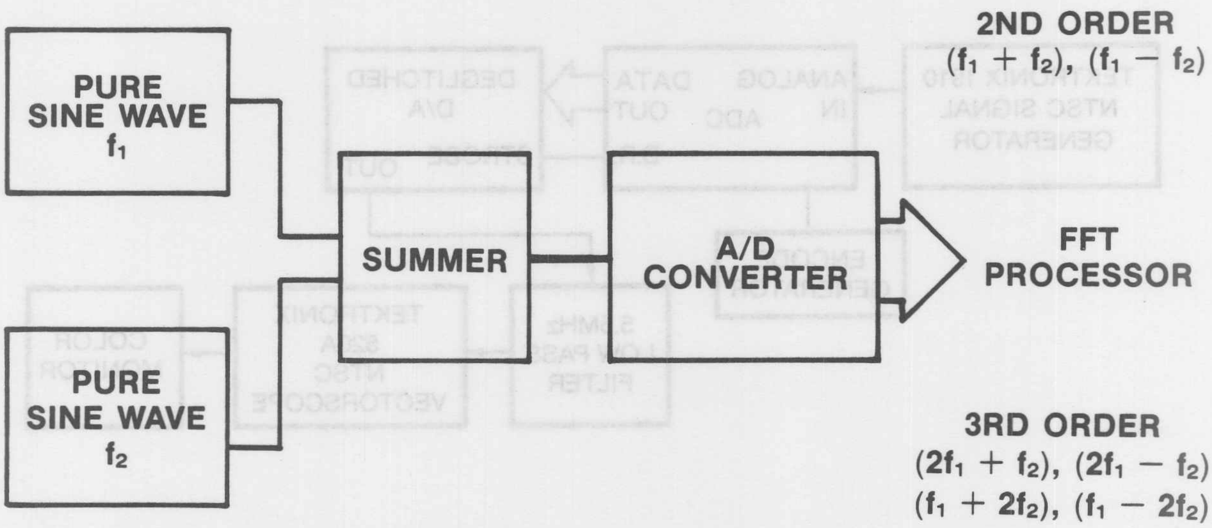
If an analog analyzer is used as illustrated here, a D/A converter is used to reconstruct the analog signal and its characteristics gets in to the measurement loop. Needless to say, it should have much better linearity than the A/D being characterized.

Using a Fast Fourier Transform is the preferred method since it is not limited by D/A converter linearity error.

Implementation of a sinewave with sufficient purity requires some care and may be the most difficult instrumentation task in this setup. Its own harmonics must be considerably lower than those generated by then converter being tested. The S/N measurement requires very good stability (and low phase jitter for the convert command clock).

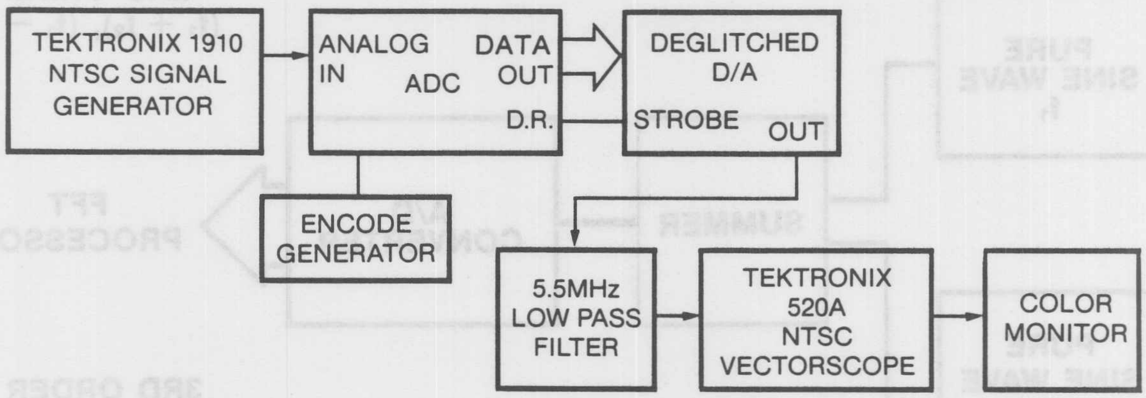
Signal-to-noise ratio is measured by the same FFT setup. First the sine wave power is computed. Then a band-stop filter at the sinewave frequency is switched in, removing the fundamental signal; and the total remaining power is computed. An ideal A/D converter with a full scale ideal sinewave input has a theoretical signal-to-noise ratio of (6n + 1.8)dB where n is the number of bits.

INTERMODULATION DISTORTION



125 The test for INTERMODULATION DISTORTION is similar but requires two spectrally clean signal generators.

Differential Gain and Phase



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125A This specification is used specifically for video and television applications.

Differential Gain and Phase are defined as the percentage difference between the output amplitudes (and phase) of a small high-frequency sinewave at two levels of a low frequency signal on which it is superimposed.

A differential gain error describes a change of the color subcarrier amplitude as a function of the luminance. The effect is a variance in color saturation between light and dark portions of a video picture.

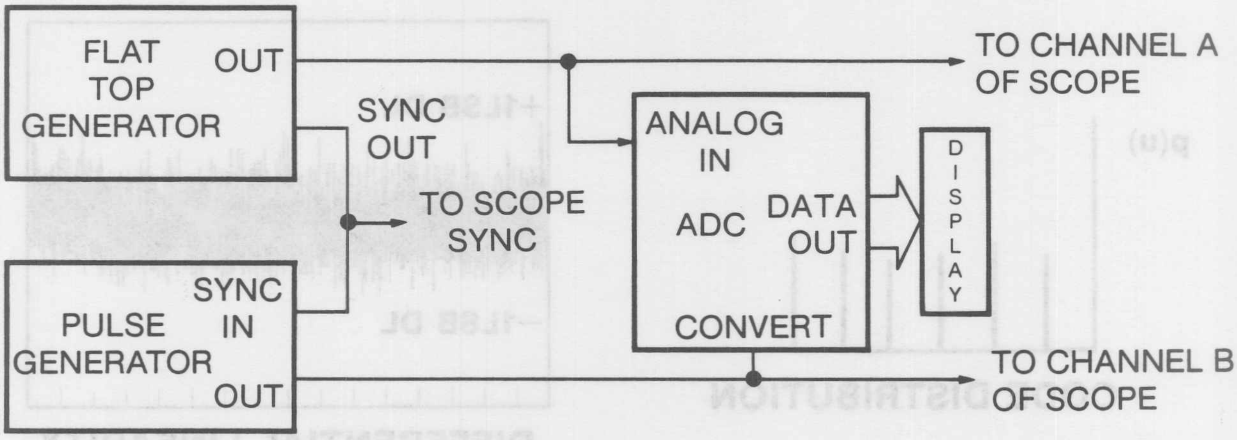
Differential phase error describes a phase modulation of the chrominance caused by a change in luminance level. If the differential phase is high, the hue in the resultant picture will vary with scene brightness.

A typical test setup is shown here. Specialized test equipment is required.

REFERENCE:

"IEEE STANDARDS FOR PERFORMANCE TESTING OF A/D & D/A CONVERTERS in PCM TV and Video Circuits"

Transient Response



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125B TRANSIENT RESPONSE is defined as the time needed for an A/D converter to achieve its rated accuracy after a full scale step is applied to its input.

A test setup is shown here. The pulse generator that generates the "convert command" is synchronized to a flat-top pulse generator. A high-frequency dual-trace oscilloscope is connected as shown and synchronized to the pulse generators.

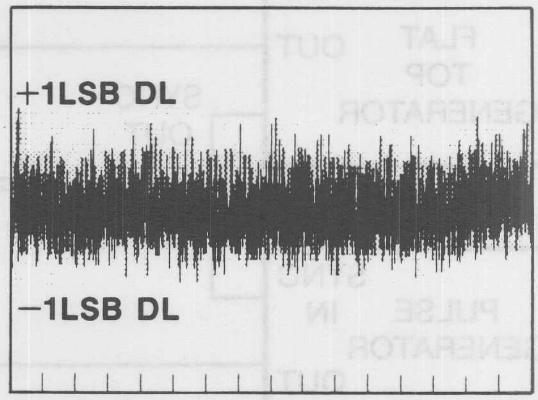
The flat-top pulse generator is adjusted for a voltage output of slightly less than full scale as observed on the display.

The "convert" pulse is adjusted in time relation to the flat-top pulse. The time setting is noted when the display indicates the output word is within 1 LSB of the original value.

The amount of time from transition of the flat-top waveform to the leading edge of the "convert" command is the "transient response" settling time.

A/D STATISTICAL CHARACTERISTICS

CODE DISTRIBUTION



DIFFERENTIAL LINEARITY

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126 Other characteristics of A/D converters that may be of interest are the probability distribution of the output codes and a histogram of the DIFFERENTIAL LINEARITY ERROR.

The code probability distribution is not a specification but is sometimes used as a characterization test.

A typical histogram of an ultra-high speed A/D converter will be shown in a later diagram.

16-BIT RESOLUTION
14-BIT ACCURACY

WHAT DOES THIS MEAN?

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127 Even though a converter may have 16-bits of resolution it may be specified for linearity that corresponds to what one would expect from a 14-bit converter. This fact bothers many engineers.

In the early days of converter design, when the first monolithic sub-components were available, the D/A switches were available in quads. Industry standard pinouts (such as DAC70, 71 and 72 and ADC71 and 76) were defined ten years ago. Resistors, especially thin-film resistors, were adequate for 14-bit parts that could be manufactured in volume and remain accurate over a reasonable life.

In many applications, the two bits may appear to be useless are indeed useful. In signal analysis and audio applications, the additional resolution results in added spectral purity even though the 16-bit resolution converter might have a 14-bit linearity specification. The presence of the "extra" bits result in less distortion particularly at low signal levels.

WHAT CODES ARE REQUIRED?

- Unipolar Straight Binary (USB)
- Bipolar Offset Binary (BOB)
- Binary Twos Complement (BTC)
- Binary Coded Decimal (BCD)

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128 Converters are available with several code configurations. The most popular are BOB or BTC for bipolar signals. BCD coded converters are mostly integrating types used in panel meters and digital voltmeters.

There are COMPLEMENTARY codes to those above. They are labeled CSB, COB, CTC and CDC respectively. These are merely the logic inversion of the "true" binary codes.

SAMPLE/HOLD AMPLIFIERS

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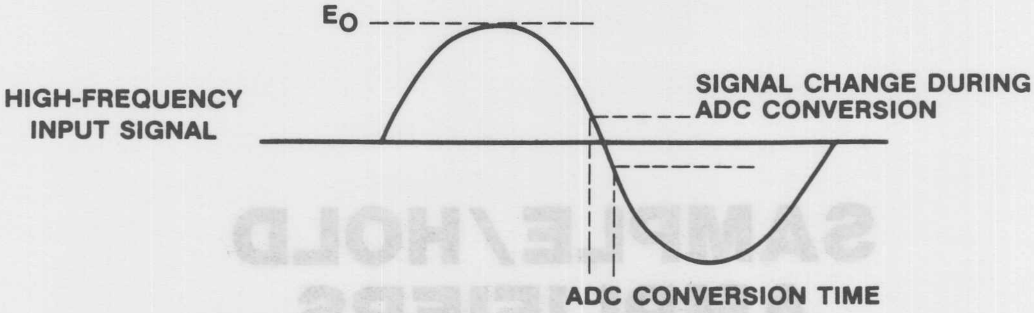
129 Achieving the full speed and accuracy capabilities of successive approximation converters requires the use of a sample-hold amplifier.

Burr-Brown Sample-holds:

SHC298	Use with ADC574A, 674A, 80, 804
SHC5320	Use with ADC674A, 84, 85H, 87H, 803
SHC803, 804	Use with ADC803
SHC76	Use with ADC71, 76, PCM75

WHY USE A SAMPLE/HOLD?



SIGNAL SHOULD REMAIN CONSTANT DURING A/D CONVERSION

ASSUME: 1/2LSB OF CHANGE IN INPUT SIGNAL IS ACCEPTABLE DURING ADC CONVERSION

$\pm$10V P–P WAVEFORM

1.5μsec ADC CONVERSION TIME [12-BIT RESOLUTION]

THEN: $1/2\text{LSB} = 1/2 \bullet \frac{20\text{V}}{4096} = 2.44\text{mV}$

$2.44\text{mV} \div 1.5\mu\text{S} = 1.627\ \text{V/mS}$ = MAX RATE OF CHANGE OF INPUT SIGNAL WITHOUT S/H

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130 The input signal must be constant during A/D conversion. If a sample-hold is not used, we have the situation illustrated above.

Assuming that less than 1/2LSB change of the input is the maximum acceptable change, only a 1.627V/ms input slew rate can be tolerated for a 12-bit A/D converter that has a 1.5us conversion time. This corresponds to +-10V sinewave with about a 26 Hz frequency! This is a disappointingly low frequency for a 1.5us A/D converter. Adding a sample-hold will improve this situation dramatically.

MAX INPUT FREQUENCIES

—WITHOUT SAMPLE/HOLD

$$\left(\frac{d}{dt}\right)max = \frac{d}{dt}(E_o \sin 2\pi ft) = 2\pi f E_o$$

$$f_{max} = \frac{1627}{2\pi E_o} \quad \frac{1627}{20\pi} = 25.9Hz$$

—WITH 300nsec SAMPLE/HOLD

$$f_{max} = \frac{1}{2 \times (1.5\,\mu sec + .3\mu)}$$

$$= \underline{278kHz}$$

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131 The maximum frequency of a +-10V input sine wave that a 12-bit 1.5us A/D converter can digitize to +-1/2 LSB is increased tremendously by using a sample-hold with a 300ns acquisition time. About a 10,000 to 1 improvement in throughput rate is achieved!

KEY SAMPLE/HOLD SPECIFICATIONS

Acquisition Time
Aperture Time
Aperture Uncertainty
Droop Rate
Nonlinearity (in Sample Mode)
Charge Offset (Pedestal)
Feedthrough
Sample-to-Hold Settling Time

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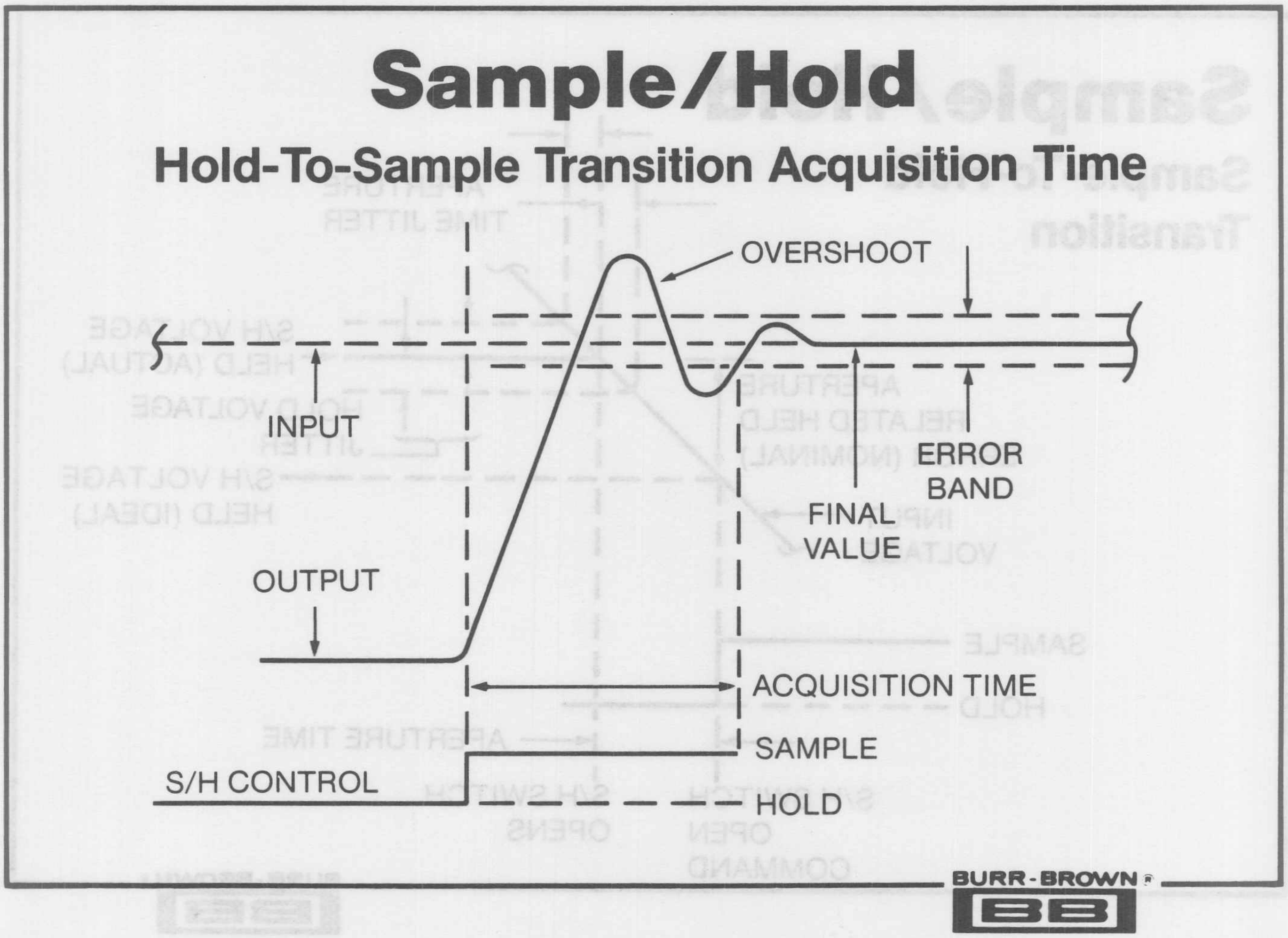
132 A sample-hold can increase the bandwidth of an A/D converter by up to four orders of magnitude while insuring that an accurate value of the signal is captured at a specific point in time.

Sample-holds are also used to optimize the speed of a multichannel (multiplexed) input data acquisition system. The multiplexer can access and settle to the next channel while the S/H is holding and the A/D is converting.

A sample-hold amplifier is a device that has more specs than most A/D converters they are used to assist. Not are there only static and dynamic specs in the HOLD mode and the SAMPLE mode, there are a set of specifications for the transition from SAMPLE-to-HOLD and from HOLD-to-SAMPLE.



133

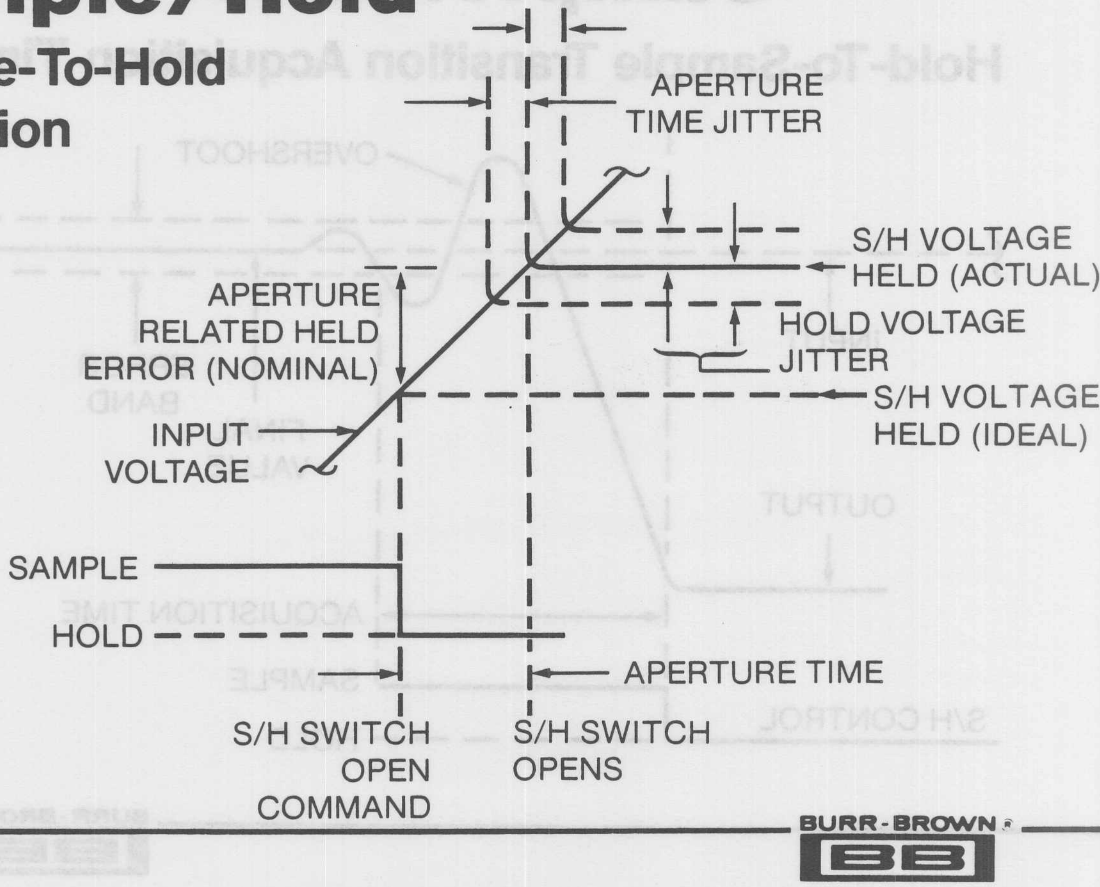
ACQUISITION TIME is a spec most often associated with a sample-hold because this spec is often the advertised speed spec.

ACQUISITION TIME is the time required for the S/H to acquire and to track the input signal after the SAMPLE command. Since this time is far longer than the aperture time, it is the time spec, along with the A/D conversion time, that limits the sampling rate of the system.

The effect of ACQUISITION TIME on HARMONIC DISTORTION of the sampling system is somewhat forgiving. The acquisition time that is allowed can be shortened to less than the time specified in the data sheet without severely affecting the AC performance of the S/H-A/D combination.

Sample/Hold

Sample-To-Hold Transition



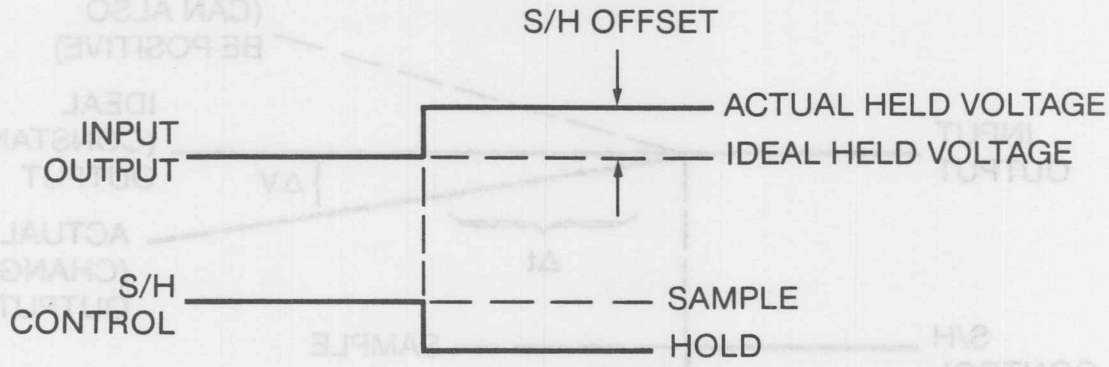
133A A great mystery about sample-hold performance is: "Exactly when, after I gave it the command to HOLD, did the circuit get the sample?" Next: "Did it get the sample accurately?"

The answer to the first question depends on two specs, APERTURE DELAY and APERTURE UNCERTAINTY. There is a delay from the time the command is issued and the time the sampling actually takes place - and one cannot see when this occurs on an oscilloscope: The SAMPLE-to-HOLD transient gets in the way. There is also uncertainty in this switching time due to noise in the switching threshold of the S/H logic. APERTURE UNCERTAINTY is one of the irreducible errors of the sample-hold performance.

This slide shows how APERTURE DELAY creates an error in the voltage held. As an example consider an input signal with a rate-of-change of 1V/us which is sampled with a 10ns aperture time. This will result in a 10mV sampled error due to the aperture time related dV/dt error. For the +-1V/us input signal, a 1ns APERTURE UNCERTAINTY would result in a +-1mV voltage uncertainty.

Sample/Hold

Sample-To-Hold Offset (Pedestal)



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133B The answer to the second question depends on many sample-hold specs.

We know the waveform being tracked is moving pretty fast (APERTURE DELAY affects the result) and we know there is APERTURE UNCERTAINTY. This has been discussed above.

There is probably phase shift (small-signal bandwidth in the SAMPLE-mode spec affects this) during SAMPLE mode.

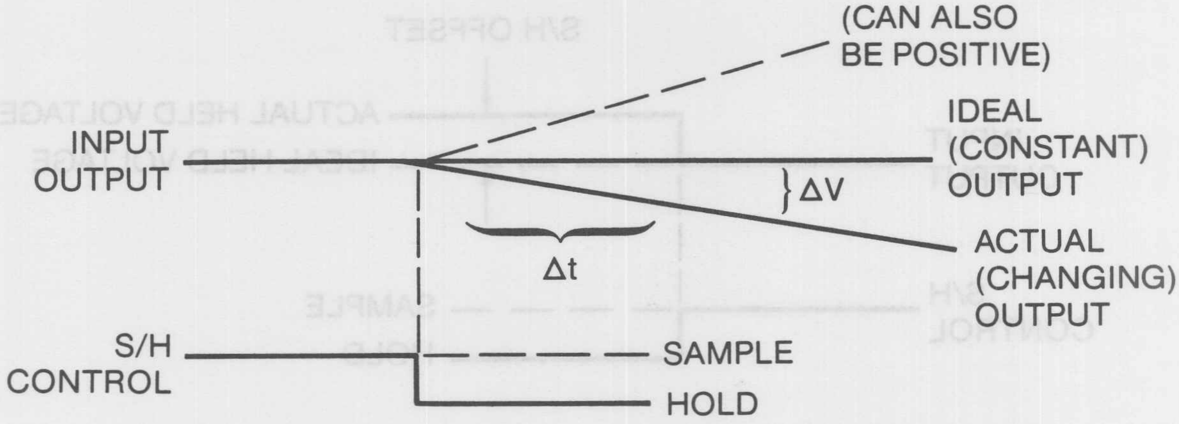
Incidentally, SMALL SIGNAL BANDWIDTH (in the SAMPLE mode) is an important spec because it gives one an indication of the phase shift added to the input signal. The small signal bandwidth should be 5 to 10 times the Nyquist frequency for minimum effect in DSP applications.

There is some charge transfer from the switch to the HOLD capacitor (the CHARGE OFFSET or the OFFSET PEDESTAL spec illustrated in this slide).

Incidentally, a small PEDESTAL is desirable, but more important is the need for a PEDESTAL that has a constant value over the signal range. If it is not constant, it will add harmonics to its AC performance in DSP applications.

Sample/Hold

Droop



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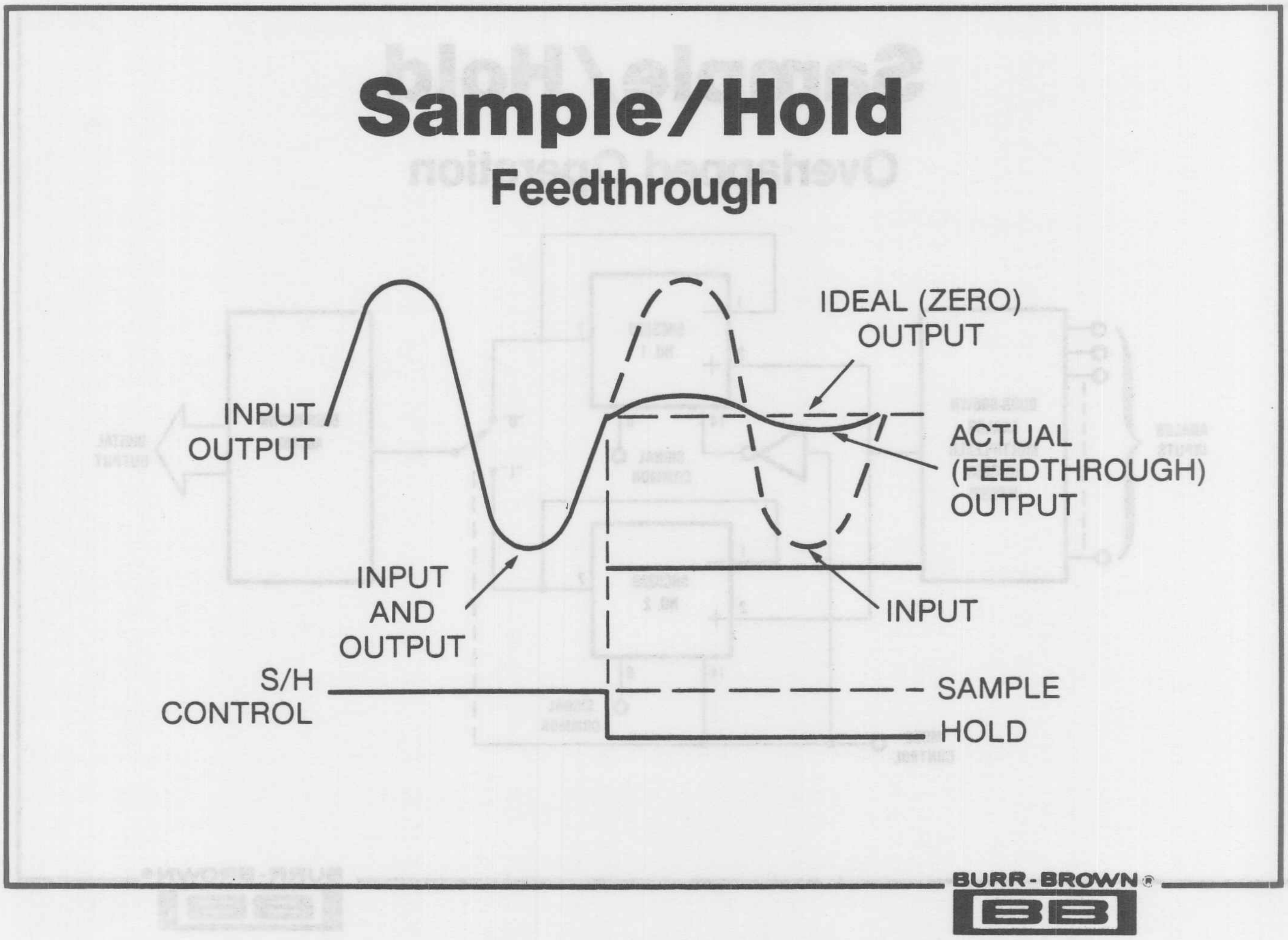
133C Now we see the value drifting away (DROOP spec) shown here. Excessive DROOP can also add harmonics to the AC performance.



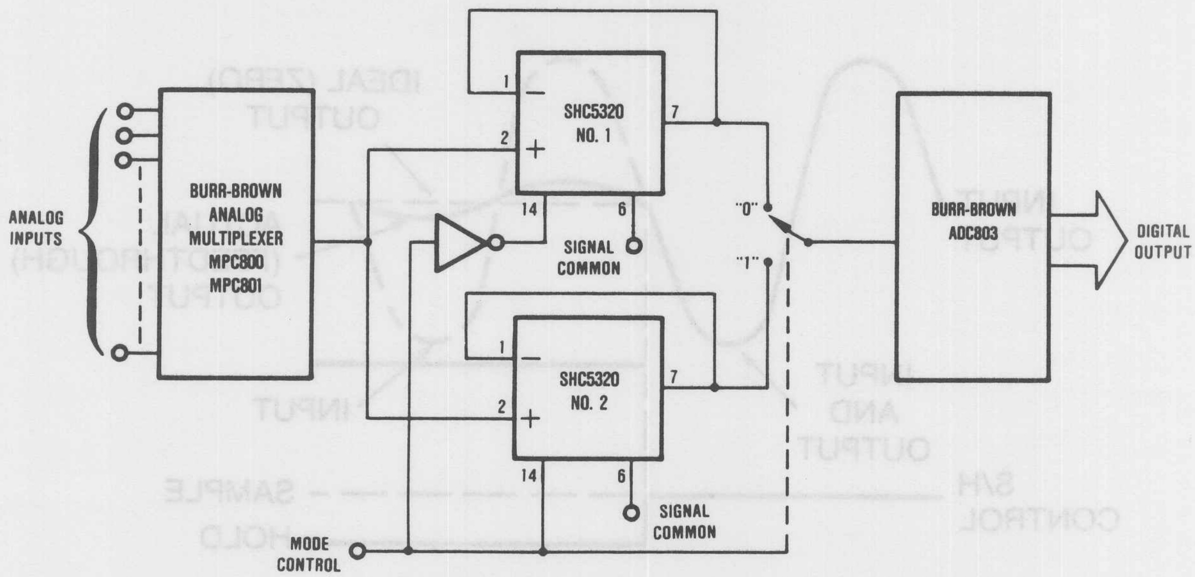
133D And, there is some ripple on it at the same frequency as the input signal (FEEDTHROUGH spec)! Needless to say, excessive feedthrough will also add unwanted artifacts to the AC performance.

Testing S/H with DC input signals is straightforward and fairly unambiguous. The AC performance of a S/H is complex. And it depends significantly on the properties of the input signal. The best way to get a handle on the high speed performance of the S/H is to ignore the specs, for the moment, and hook it to an A/D converter. Apply known waveforms that simulate, perhaps only in frequency and amplitude, the waveform of the application. Take the digital data and analyze it.

Manufacturers are now beginning to characterize S/H and A/D together and even spec them that way. It will be easier on all of us!

Sample/Hold

Overlapped Operation



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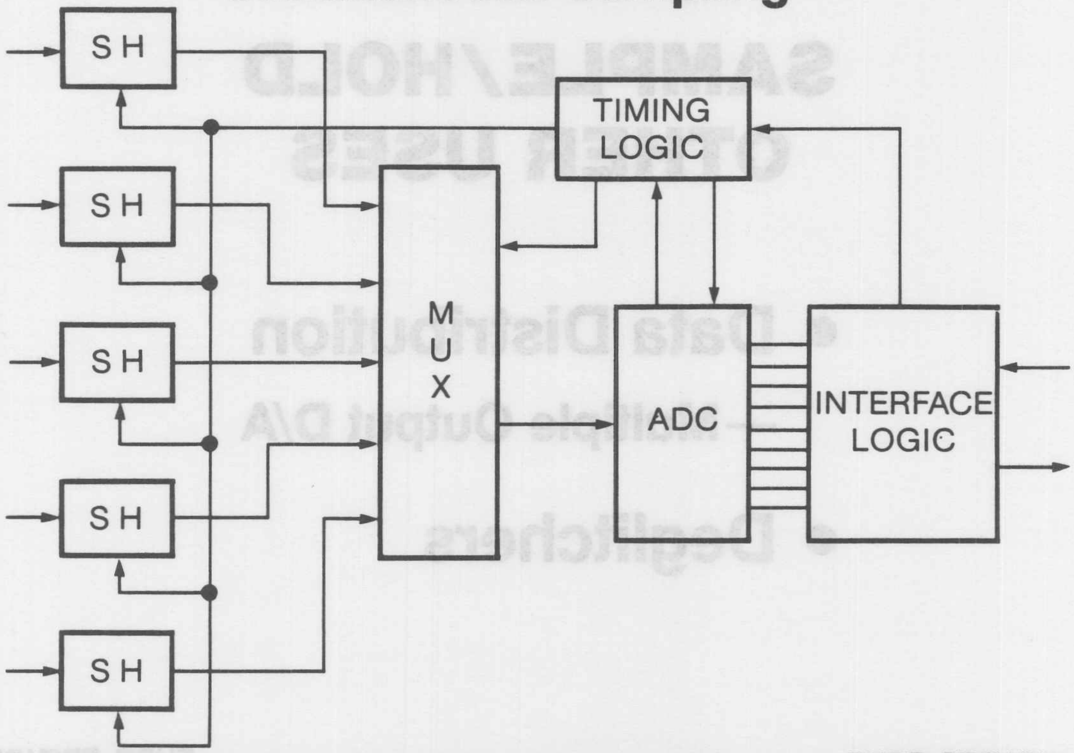
134 Two sample-holds are often used to reduce the overall acquisition time of the sampling process. One S/H is acquiring while the other is holding. This is sometimes call the ping-pong technique.

Sample/Hold

Simultaneous Sampling



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134A Another multiple sample-hold technique is simultaneous sampling - required when one A/D is used to convert several signals at one time.

SAMPLE/HOLD OTHER USES

- **Data Distribution**
  - —Multiple Output D/A
- **Deglitchers**

BURR-BROWN

135 Multiple outputs derived from a signal D/A are implemented using several sample-holds at the output. The sample-holds must constantly be updated because of DROOP. D/A converters these days are so inexpensive that this technique is virtually no longer used in new designs.

A deglitcher application will be discussed later.

12-BIT DATA CONVERTERS

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136 12-bit resolution A/D and D/A converters are a popular choice in a wide range of applications today. All moderate speed D/A converters are monolithic using either bipolar or CMOS technology and with varying degrees of completeness of the function, i.e., references, output amplifiers and microprocessor bus interfaces.

The prices of monolithic 12-bit converters today are such that one can reasonably improve the performance of designs that, in the past, have used 10-bit or even 8-bit D/A converters.

IMPORTANT D/A SELECTION CONSIDERATIONS

Are external parts are required to complete the function? What do they cost and how much space to they require?

For instance, most converters have provisions for an external GAIN and OFFSET (or ZERO) adjustment. Some require precision resistors or at least ones with matched temperature coefficients. And some require an external op amp or two to complete the function.

<u>Reliability/Qualification</u> Does the vendor perform qualification studies on his parts? Can I get the reports? Can I accept the vendor's qualification instead of doing my own?

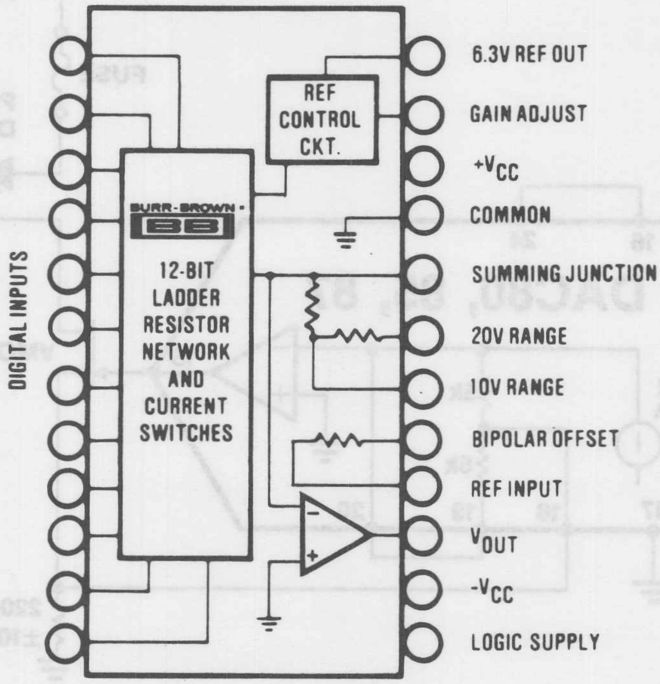
<u>Package</u> Converters, especially monolithic converters are available in a variety of packages, ceramic DIP, plastic DIP, and SOIC. There will be more and more available in plastic SOICs in the next year especially the models with volume potential.

<u>Power Dissipation</u> A wide range is available from a few tens of milliwatts (CMOS, minus the external parts) to a few 100 milliwatts for a complete bipolar converter with voltage output and 3 to 5us settling time. Complete high speed converters may dissipate 1 to 2 watts.

<u>Second sources</u> Second sources do exist for the more popular models. Most converters especially high speed converters are sole sources. For some companies, the customer service aspects of vendor performance has become as important as product performance.

<u>Price</u> Low volume catalog prices have been fairly firm over recent years but prices on volume purchases have dropped significantly over the last 2 or 3 years for medium performance 12-bit converters. The price in the DATA BOOK or in the DATA SHEET does not fully reveal the price possibilities at higher volumes.

DAC80, 85, 87 FAMILY
12-BIT MONOLITHIC CONVERTERS



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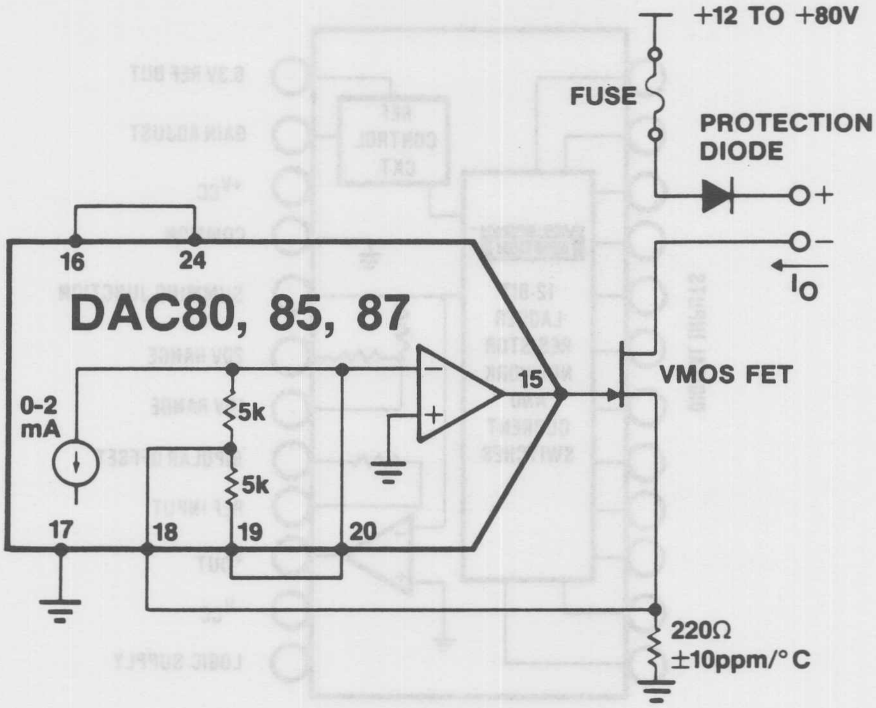
137 This family was designed by Burr-Brown in the mid-seventies and is the most widely second sourced 12-bit D/A - except perhaps for the DAC7541 CMOS D/A.

It is truly an industry standard for complete 12-bit D/A converters. All DAC80, 85 and 87 are now monolithic.

0-20mA OUTPUT 12-BIT D/A



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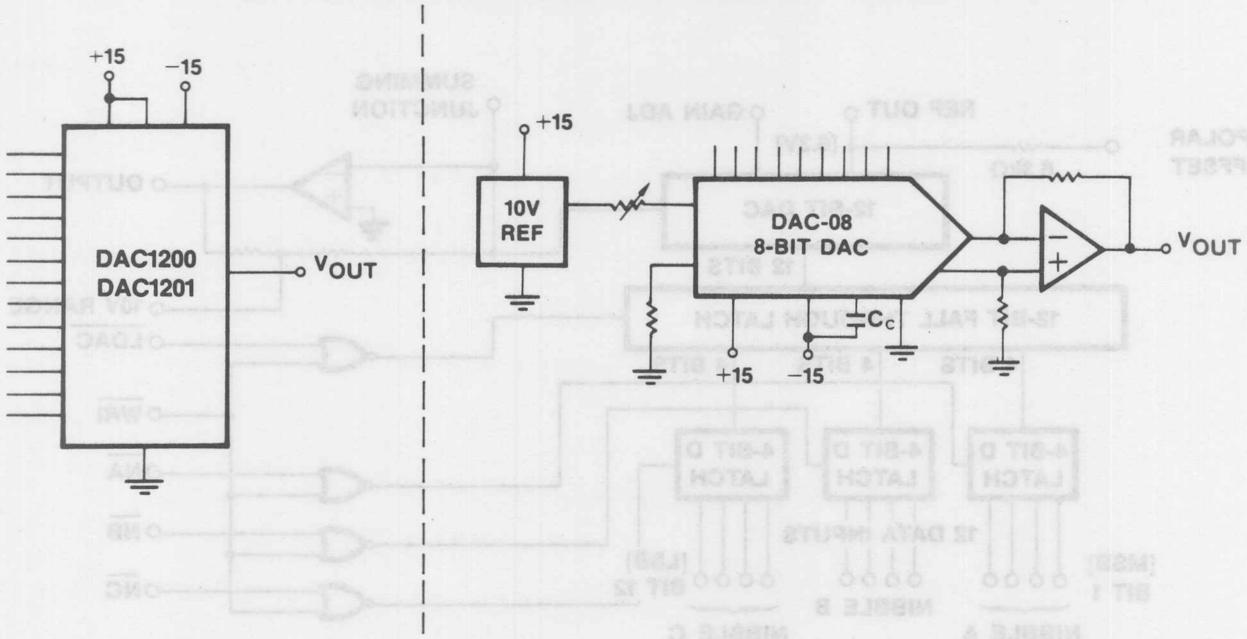
138 Since the DAC80 family has an uncommitted high gain output operational amplifier, many functions can take advantage of the op amp features of the D/A. An example is shown here.

CONSIDER A 12-BIT D/A FOR 8–10-BIT APPLICATIONS



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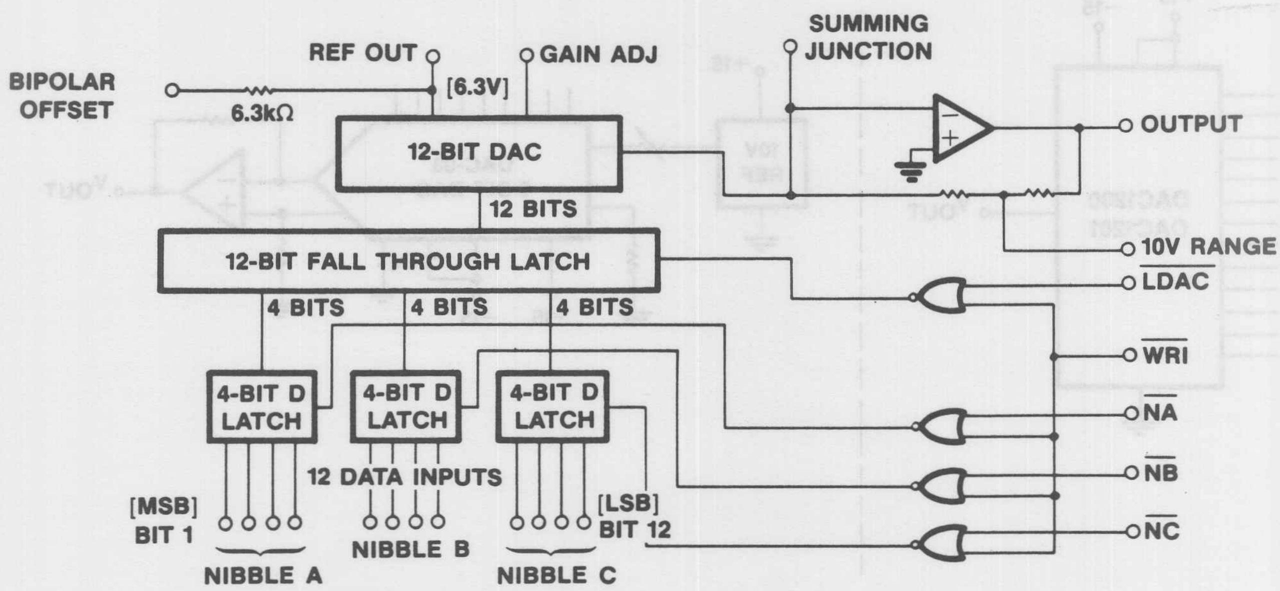
139 Because of the introduction of the Burr-Brown DAC1200 and DAC1201, it is now feasible to use a 12-bit converter in applications where 10-bit or even 8-bit converters have been used perhaps only with marginal overall instrument or system performance.

A DAC1200 or a DAC1201 (with microprocessor interface) can virtually be used in 8-bit applications with no external components.

Shown above is a suggestion that a DAC1200 can replace a DAC-08 and all the external parts required for close to the same cost.

DAC811 FAMILY
MICROPROCESSOR COMPATIBLE
12-BIT D/A CONVERTERS



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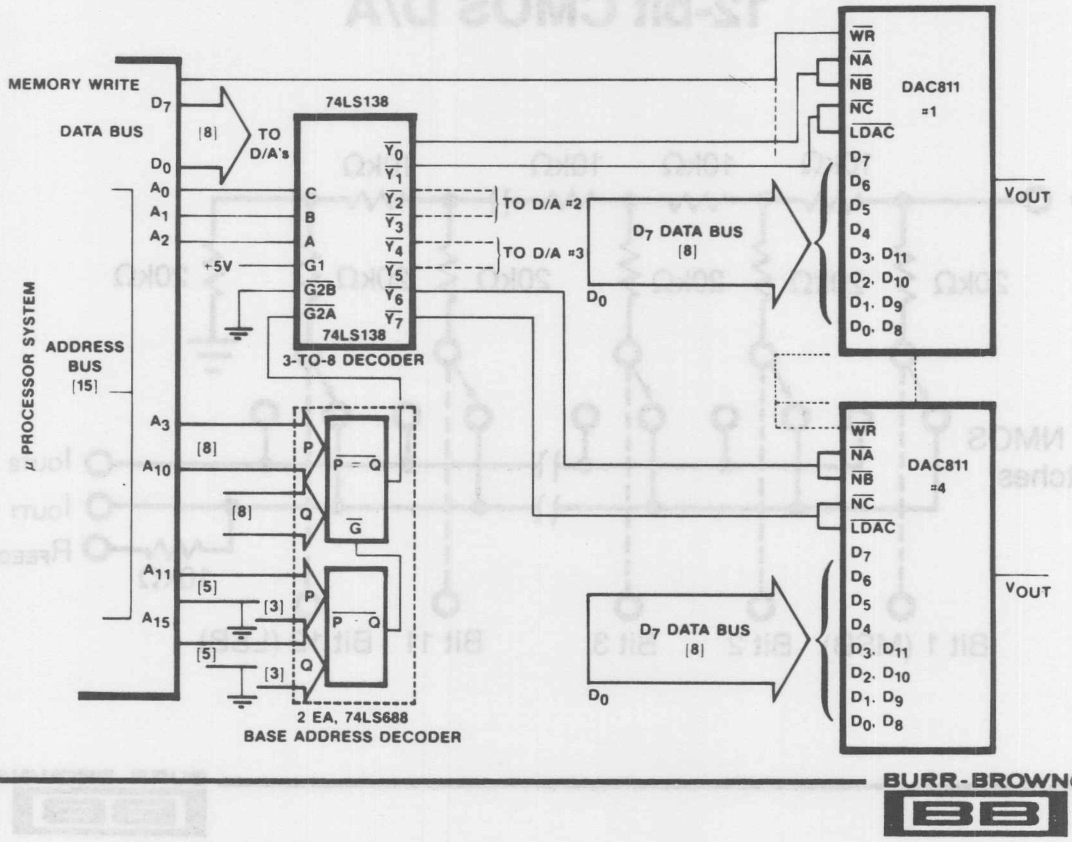
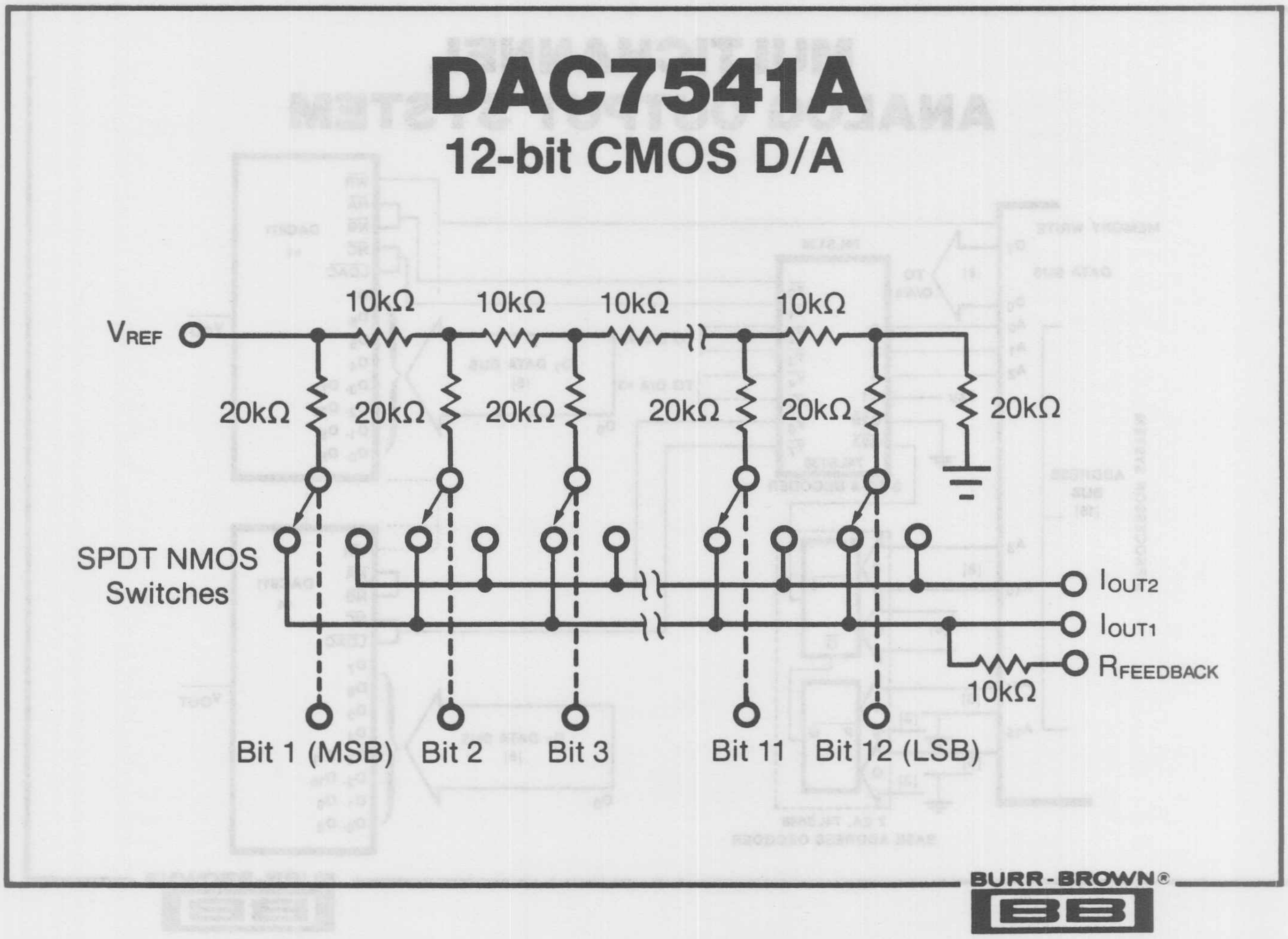
140 The DAC811 is Burr-Brown's popular 12-bit D/A with microprocessor interface. As you can see the digital input structure is quite flexible. It is also available in dice form and in a plastic SOIC package.

FEATURES	BENEFITS
* flexible digital interface	* can interface to many bus configurations
* high speed output op amp	* fast settling
* single chip	* high reliability and low cost
* DIP ceramic, plastic and SOIC	
* K, B and S grades have 1/4 LSB linearity specs for precision applications	

MULTICHANNEL ANALOG OUTPUT SYSTEM



141 This is a complete connection diagram illustrating a microprocessor interface to 4 DAC811's. No other analog components are required and external digital components required have been minimized. This reduces system cost and board space and increases reliability.

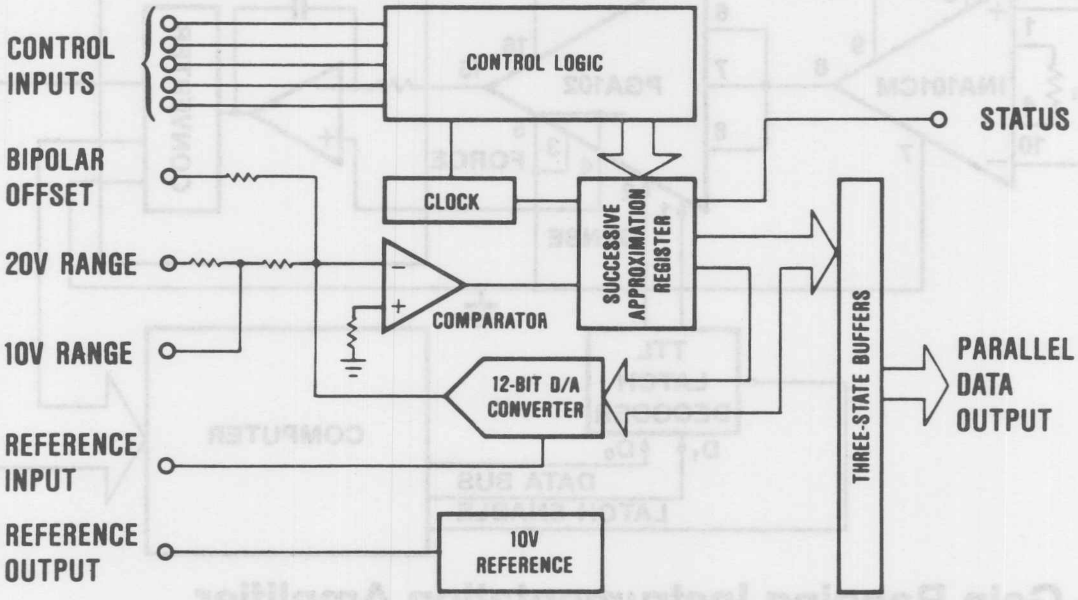


141A Burr-Brown is developing CMOS products right now. And we are also working on a BI-MOS process for future generations of converters.

Our first product is the popular DAC7541A. Although this part is specified with a +15V power supply it performs equally well at +5V. It was designed to be latch-up resistant and ESD resistant.

It is available in plastic DIP, plastic SOIC as well as ceramic DIP packages.

ADC574
μP COMPATIBLE ANALOG-TO-DIGITAL CONVERTER



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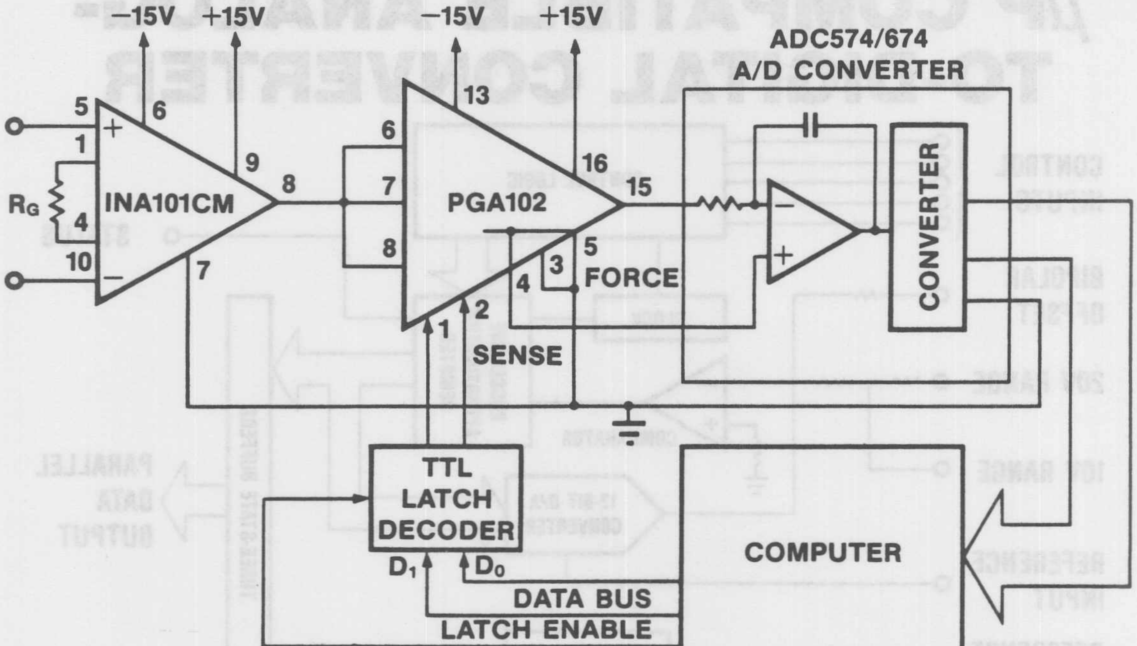
142 The ADC574A is an industry standard 25 us, 12-bit A/D converter with microprocessor interface. It is complete with reference, clock, and bus interface. It is available from several sources. This part is probably the most popular 12-bit A/D function in use today.

The ADC674A is a 15 us 12-bit A/D in the same pinout as the ADC574A.

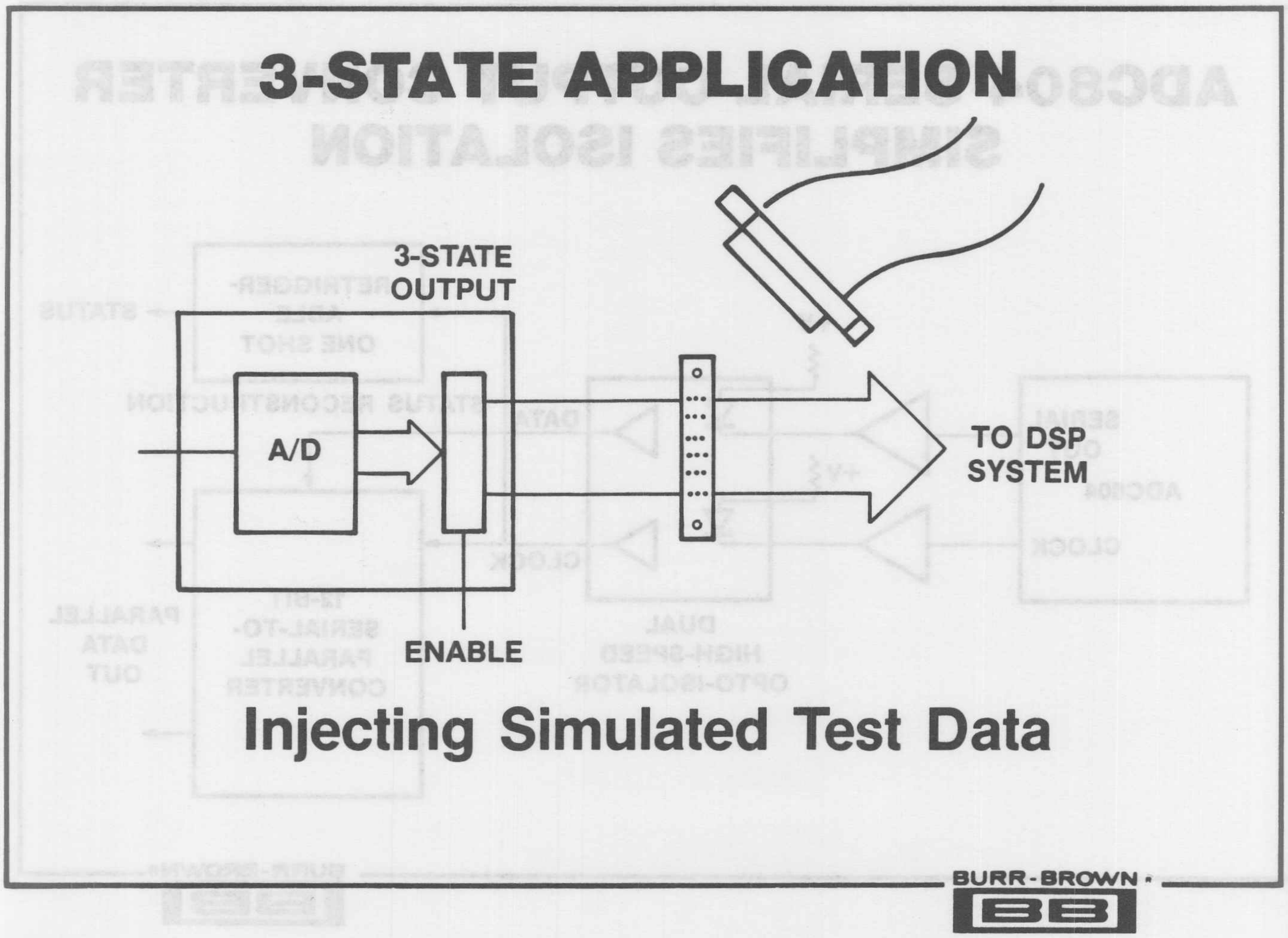
The power dissipation of the Burr-Brown part is lower than some other available designs.

ADC574



Auto-Gain Ranging Instrumentation Amplifier

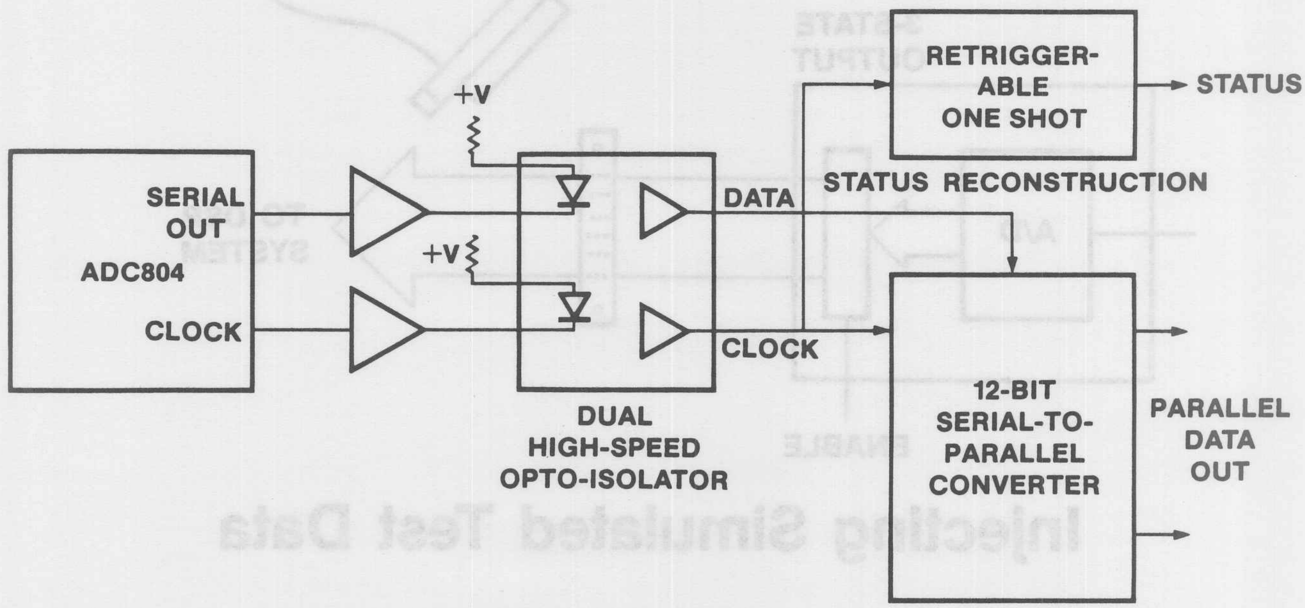
143 ADC574A/674A microprocessor interface eases the implementation of computer controlled systems. The auto gain ranging circuit shown here features the PGA102 which can be programmed for gains of 1, 10, or 100 to implement floating point conversions. This circuit is by no means complete, one could add one or two sample-holds, an analog multiplexer for a multichannel system, all under computer control.



144 An interesting use of the 3-state output of an A/D converter is to permit the injection of simulated test data into the digital portion of a DSP system.

The ENABLE signal may be nothing more than a toggle switch or a jumper mounted on the board. Or the ENABLE signal could be built-in to the test connector.

ADC804 SERIAL OUTPUT CONVERTER SIMPLIFIES ISOLATION



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145 The ADC804 was designed to provide 12-bit performance with serial output in a small package.

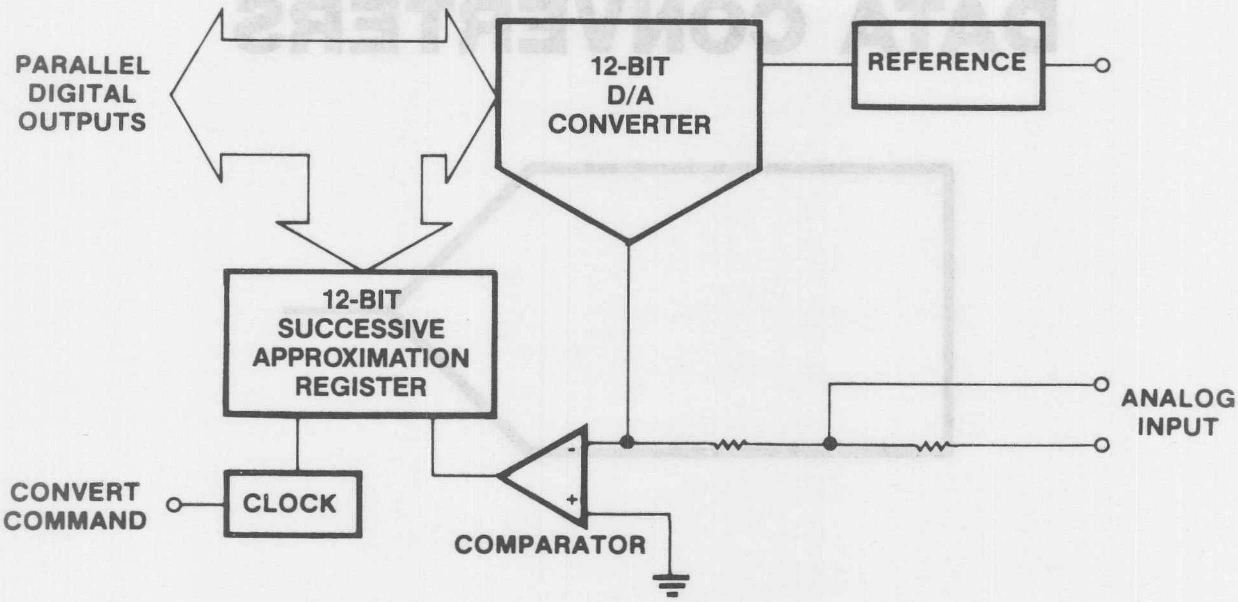
Serial data architectures are used in some systems to save board space; reduce wiring, connector size and backplane size, and to easily electrically isolate incompatible or noisy system grounds.

Note that this circuit requires only a dual opto-isolator. This is accomplished by operating the ADC804 in a continuous conversion mode and using the retriggerable one-shot to reconstruct STATUS from the clock output.

OTHER BB PARTS WITH SERIAL DATA OUTPUT

- ADC80 - 12-bit, 25us
- ADC84,85H,87H - 12-bit, 10us
- ADC803 - 12-bit, 1.5us
- ADC71 - 16-bit, 50us
- ADC76 - 16-bit, 17us
- PCM75 - audio A/D: 16-bit, 17us

ADC84/85/87
12-Bit A/D Converter



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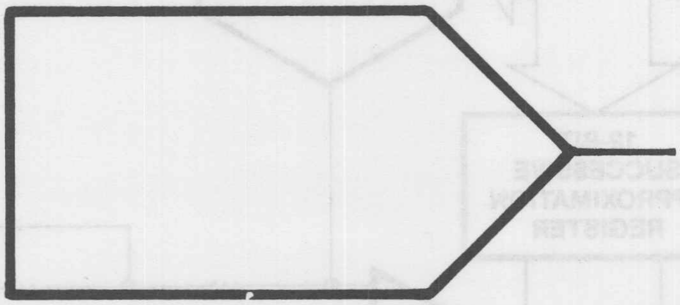
145A These popular industry standard 12-bit, 10us models are now available in chip reduced form featuring lower power dissipation and higher reliability than ever before.

16-BIT DATA CONVERTERS



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146 DESIGN AND SELECTION CONSIDERATIONS

All the design and selection considerations we discussed for the 12-bit converters section are important here plus some others. The increased resolution raises requirements that are often negligible at 12-bit and below resolutions.

- Maintaining accuracy when driving a load (D/A converters)
- Maintaining the accuracy of the source drive (A/D converters)
- Sensitivity to COMMON and supply voltage variations and noise
- Long term stability
- Minimizing noise interference from other circuits.

REFERENCE:

Burr-Brown Application Note: AN-131, "Maintaining Accuracy in High-Resolution A/D Converters", July, 1985.

A COMPLETE 16-BIT D/A CONVERTER FAMILY

	Industry Standard				Monolithic				Latched DACs				
									16-Bit Port			8-Bit Port	
	DAC 71/72 CSB-I	DAC 71/72 CSB-V	DAC 71/72 COB-I	DAC 71/72 COB-V	DAC 700	DAC 701	DAC 702	DAC 703	DAC 705	DAC 706	DAC 707	DAC 708	DAC 709
0 to −1mA Output	X				X		X						
±1mA Output			X							X		X	
0 to +10V Output		X				X							
±5V Output									X				
±10V Output				X				X			X		X
16-Bit Latch									X	X	X		
8-Bit Latch												X	X
Serial Input												X	X

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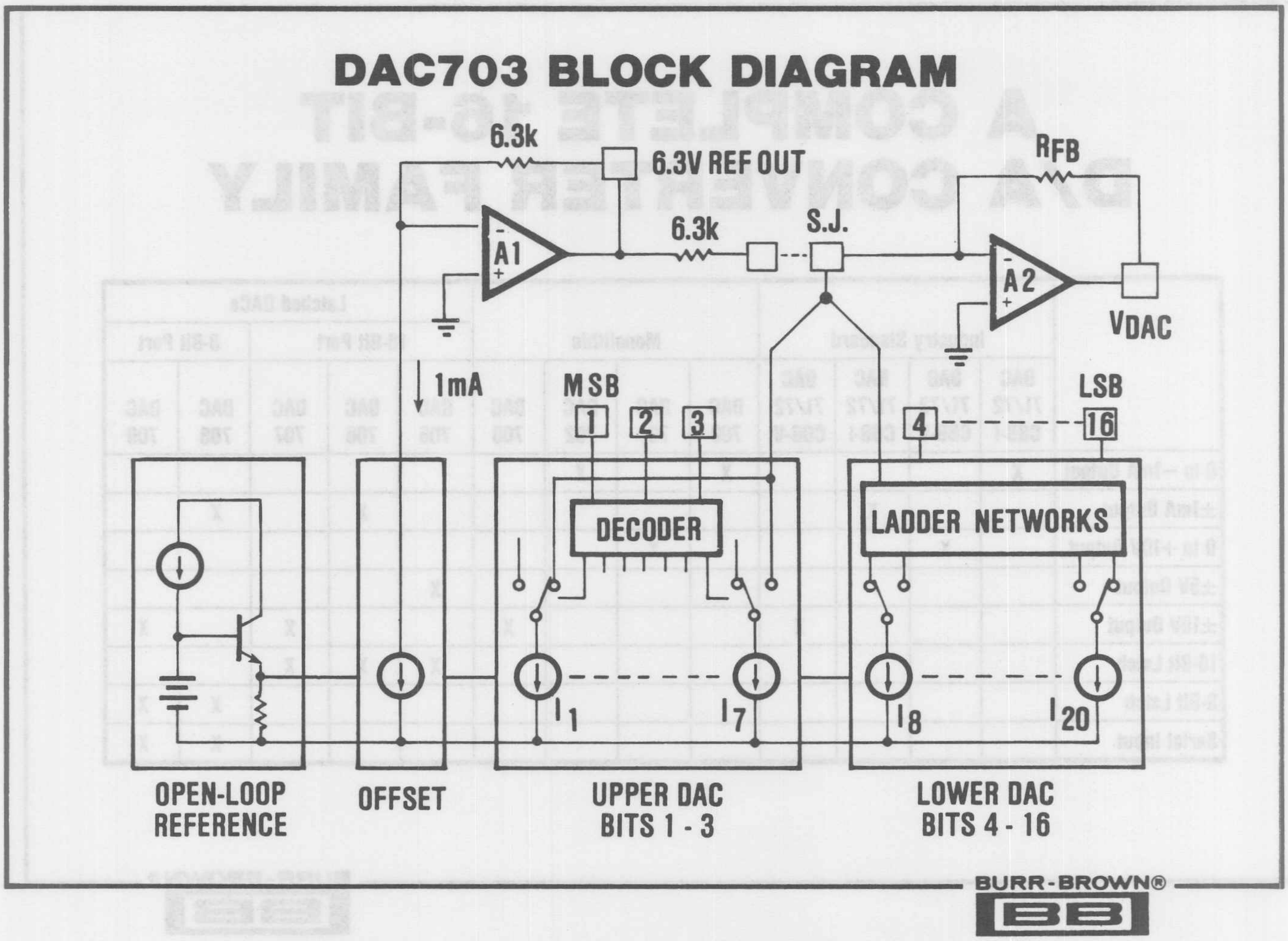
147 Burr-Brown has a broad selection of 16-bit D/A converters and it is still growing!

Not shown here are two data converters specially specified for motor control applications. The DAC710 and DAC711 specs emphasize performance around BIPOLAR ZERO.

Since this table was constructed two new low cost industrial D/As have been added, DAC1600JP and KP. More about those later.

When we add the PCM audio models to this list one can see that Burr-Brown has the most complete line of 16-bit D/A converters in the industry.

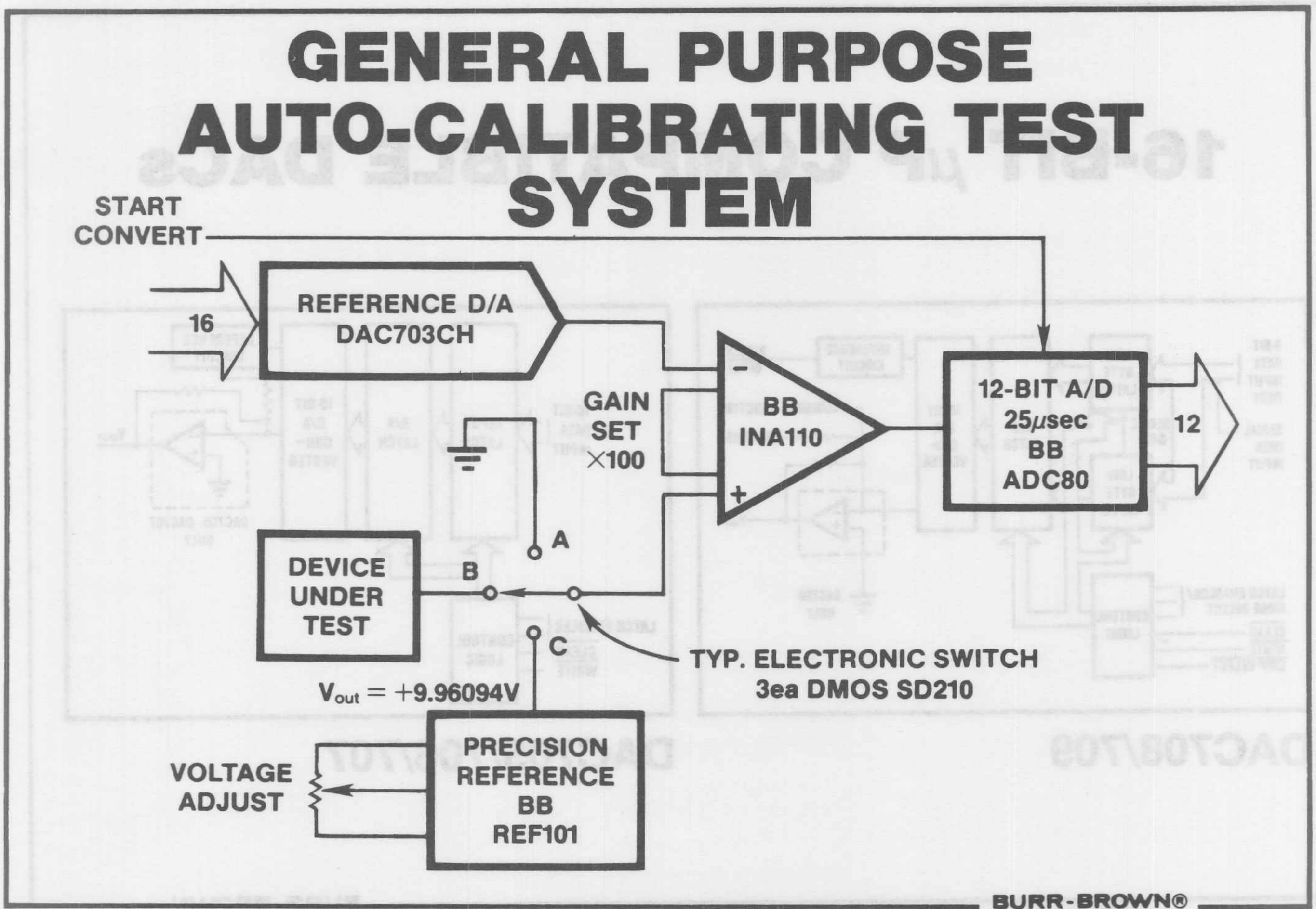


148 The DAC703 is Burr-Brown's key 16-bit converter design; the design from which most of the high resolution A/D and D/A converters is derived.

The major subcircuits of the DAC703 are: The upper D/A (bits 1-3), the lower D/A (bits 4-16), reference (subsurface zener and amplifier), bipolar offset current source and output op amp. Also shown is a dummy R-2R ladder which maintains power supply return currents at less than 20 uA for any input code.

The DAC703 features a segmented design. The most significant three bits are made up of seven individual current sources. All resistors are identical for maximum resistor ratio stability over temperature and time. This design technique assures monotonicity of the most significant bits.

The dummy ladder reduces power supply return current changes to such a low value that these parts are easy to apply from a system ground management standpoint.



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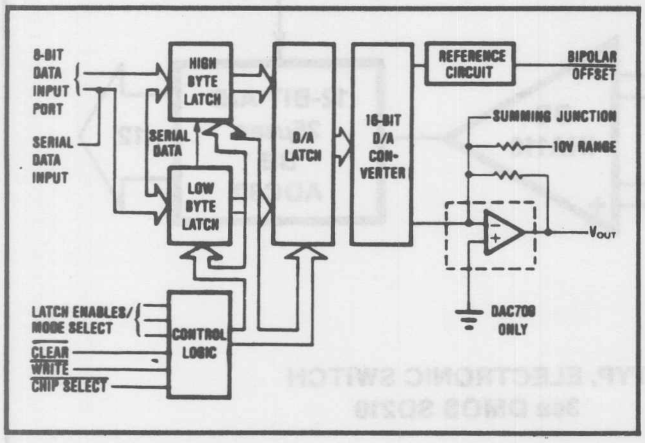
149 The DAC703LH or CH (15-bit linear at room temp, 14-bit linear over temp) make excellent choices for a general purpose tester reference due to their fast settling time and outstanding DC characteristics.

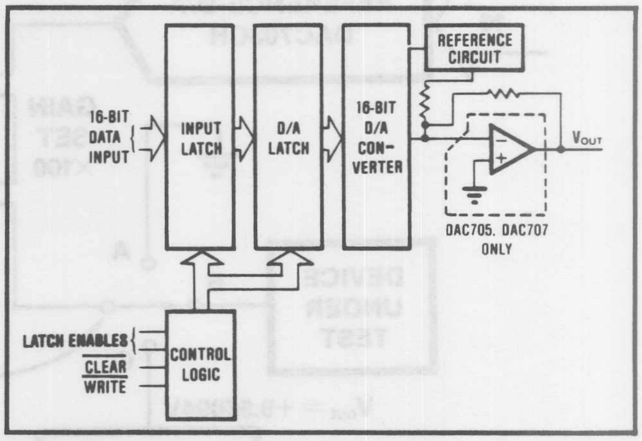
The total test time is limited by the settling time of the Device Under Test (DUT) (a 10 or 12-bit D/A ,for example), the settling time of the instrumentation amplifier, and the conversion time of the ADC. If the DUT settles in less than 50 us, then the total test time will be less than 100 us. This means that all 4096 possible output voltages of a 12-bit D/A could be measured in less than 0.5 seconds.

Software calibration can be used to remove the combined offset and gain errors of the circuit elements as shown.

16-BIT μP COMPATIBLE DACs



DAC708/709



DAC705/706/707

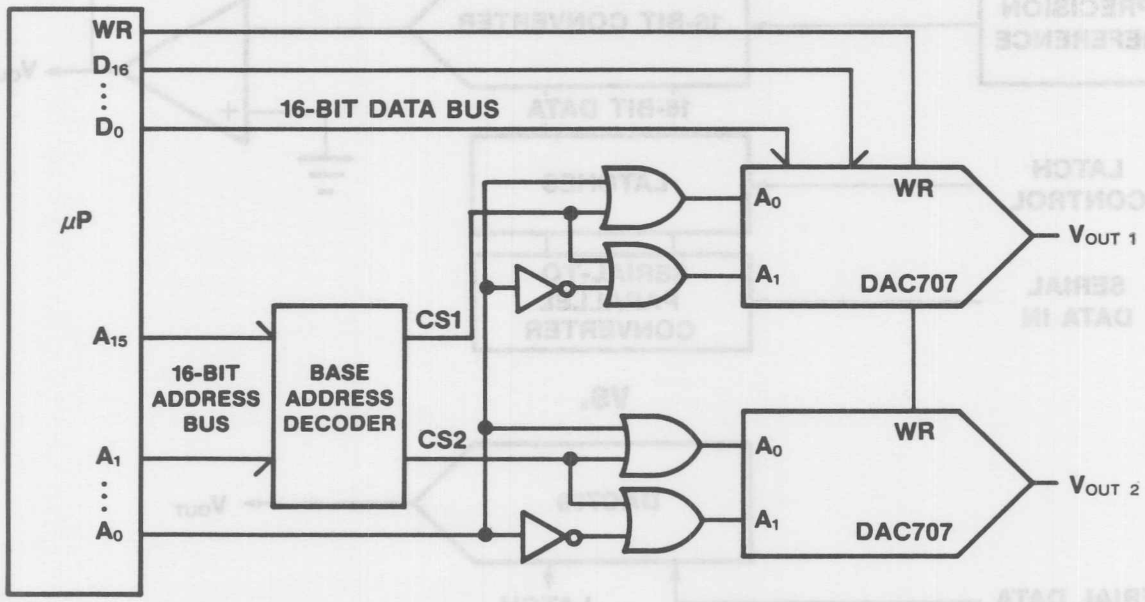
BURR-BROWN®

150 The microprocessor compatible 16-bit resolution D/A family includes the 8-bit port DAC708/709 and the 16-bit port DAC705/706,707. These parts will significantly reduce component count in D/A applications.

The DAC708 and 709 also have serial input capability.

The DAC707 (the 16-bit port model with bipolar output ranges) is now available in plastic in 13-bit and 14-bit linear grades and lower prices than ever!

μP INTERFACING OF MULTIPLE DAC707s



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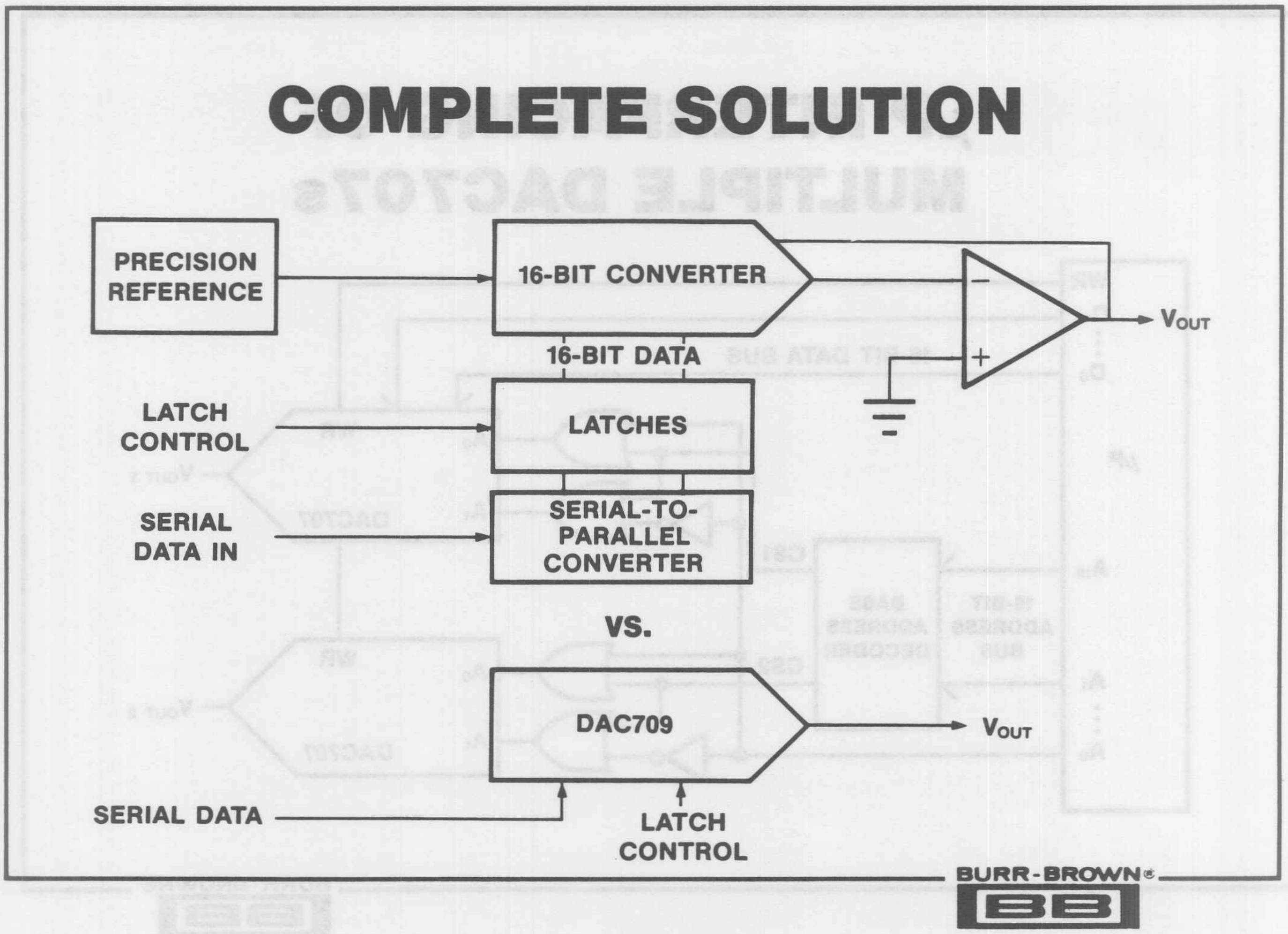
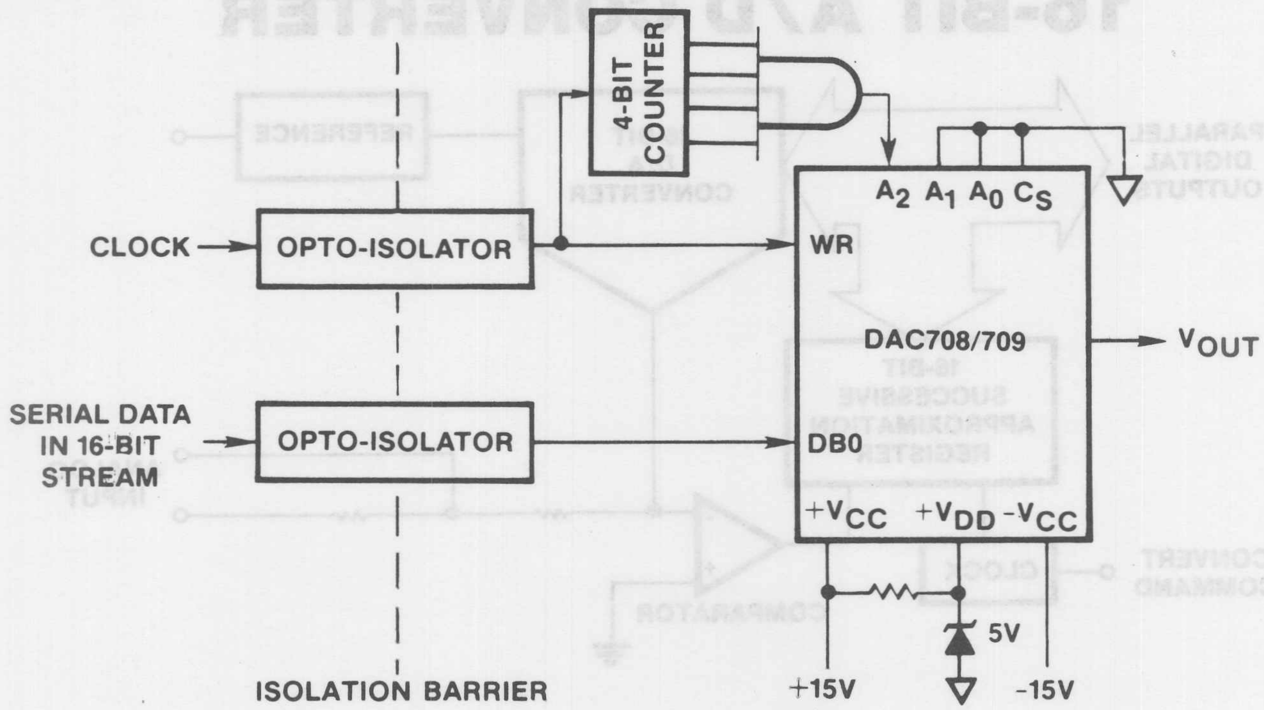
151 It is quite easy to interface multiple DAC707's to a 16-bit microprocessor bus. The application shown uses only one address line to select either the input register or the D/A register. An external address decoder selects the desired converter.



152 A complete serial input D/A such as the DAC709 will save as many as 5 IC logic packages.

SERIAL INPUT SIMPLIFIES ISOLATION



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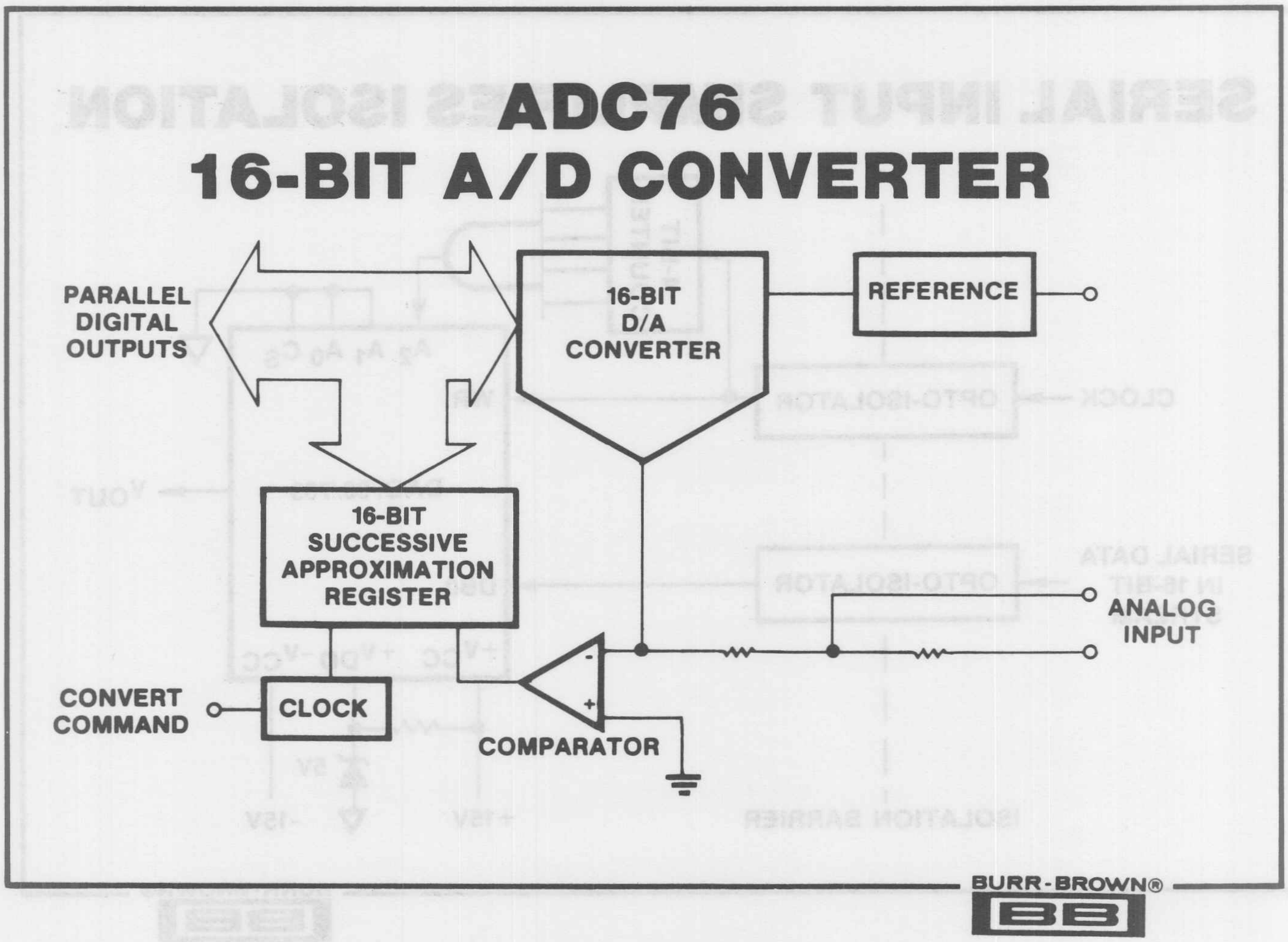
153 A serial input feature is useful for applications requiring isolation of one part of a system ground from another. Using the DAC708 and DAC709 does not require an extra 5V logic power supply.

Serial input D/A converters are also used to reduce the wiring real estate on a PC board. New designs of compact disc players now use serial input D/A's for this reason.



154 The ADC76 A/D converter from Burr-Brown in now in its second generation.

FEATURES: - 16-bit resolution - 14-bit linearity - Complete with reference and clock - 17 us conversion time

COMPANION SAMPLE-HOLD: SHC76

Consider A 16-Bit D/A For 12-Bit Applications

DAC1600

JP 13-bit linear
KP 14-bit linear

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155 Because of the introduction of the Burr-Brown DAC1600JP and KP last year, it is now feasible to use a 16-bit resolution converter in situations where 12-bit converters have been used perhaps only with marginal overall instrument or system performance.

PCM D/A

General Features and Characteristics

- 16-bit resolution
- Fast-settling (4X oversampling for audio)
- THD Specification input levels
  FS, −20dB, −60dB
- THD Grades:
  0.0025% to 0.008% at FS at 991Hz
- No drift specs
- Zero and gain specs: ±1 or ±2%

BURR-BROWN

156 Burr-Brown has been supplying D/A converters for the COMPACT DISK market for 5 years and now has greater then a 50% share of the market.

Shown above are the general characteristics and ranges of performance of Burr-Brown PCM converters.

As you can see these converters are specified for AC performance and more specifically for audio applications.

Prices are lower than the fully DC-parameter specified converters that most of us are used to.

REFERENCE:

Burr-Brown Application Note: AN-113, "Data Converter Test Methods for Digital Audio Applications", June, 1984.

PCM AUDIO

16-Bit Resolution Converters

PCM53 ±$10V_{OUT}$, ±12 to ±15V PS, 24-pin DDIP

PCM54 ±$3V_{OUT}$/±1mA I_{OUT}, ±5 to ±12V PS, 28-pin DDIP, adjustable MSB

PCM55 ±$3V_{OUT}$/±1mA I_{OUT}, ±5V PS, 24-lead SOIC

PCM56 ±$3V_{OUT}$/±1mA I_{OUT}, ±5V PS, 16-lead SDIP, serial in, adjustable MSB

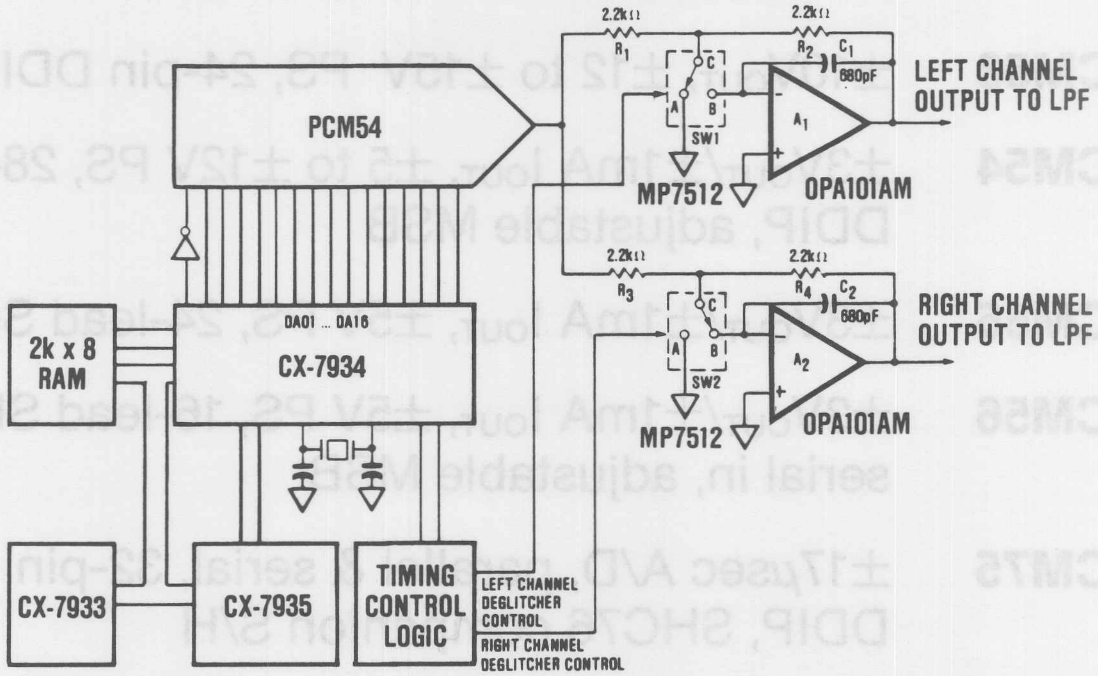
PCM75 ±17μsec A/D, parallel & serial, 32-pin DDIP, SHC76 companion S/H

BURR-BROWN

157 Above is a list of PCM D/A converters and one A/D converter.

Note that some models are available for operation on +-5V power supplies, that an SOIC package is available and that there is a serial input model.

A Single PCM54 Used to Obtain Both Left and Right Channel Output in a Typical Digital Audio System.



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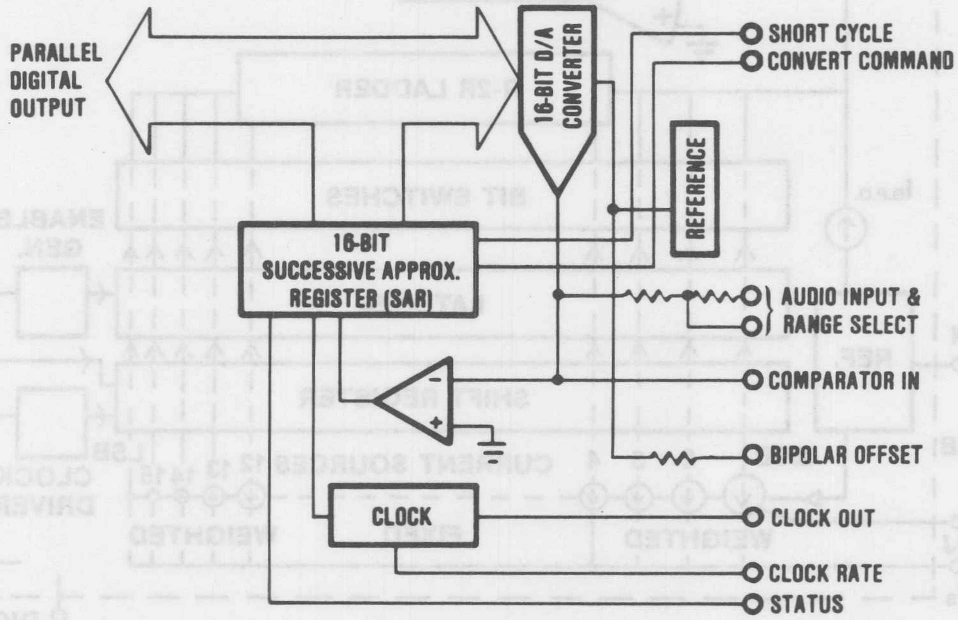
158 This is an example of a compact disc application. Burr-Brown PCM D/A converters are fast enough to allow use of a single D/A in stereo applications. In fact, the D/A is fast enough to allow 4X oversampling and stereo.

PCM75
16-BIT HYBRID AUDIO ADC



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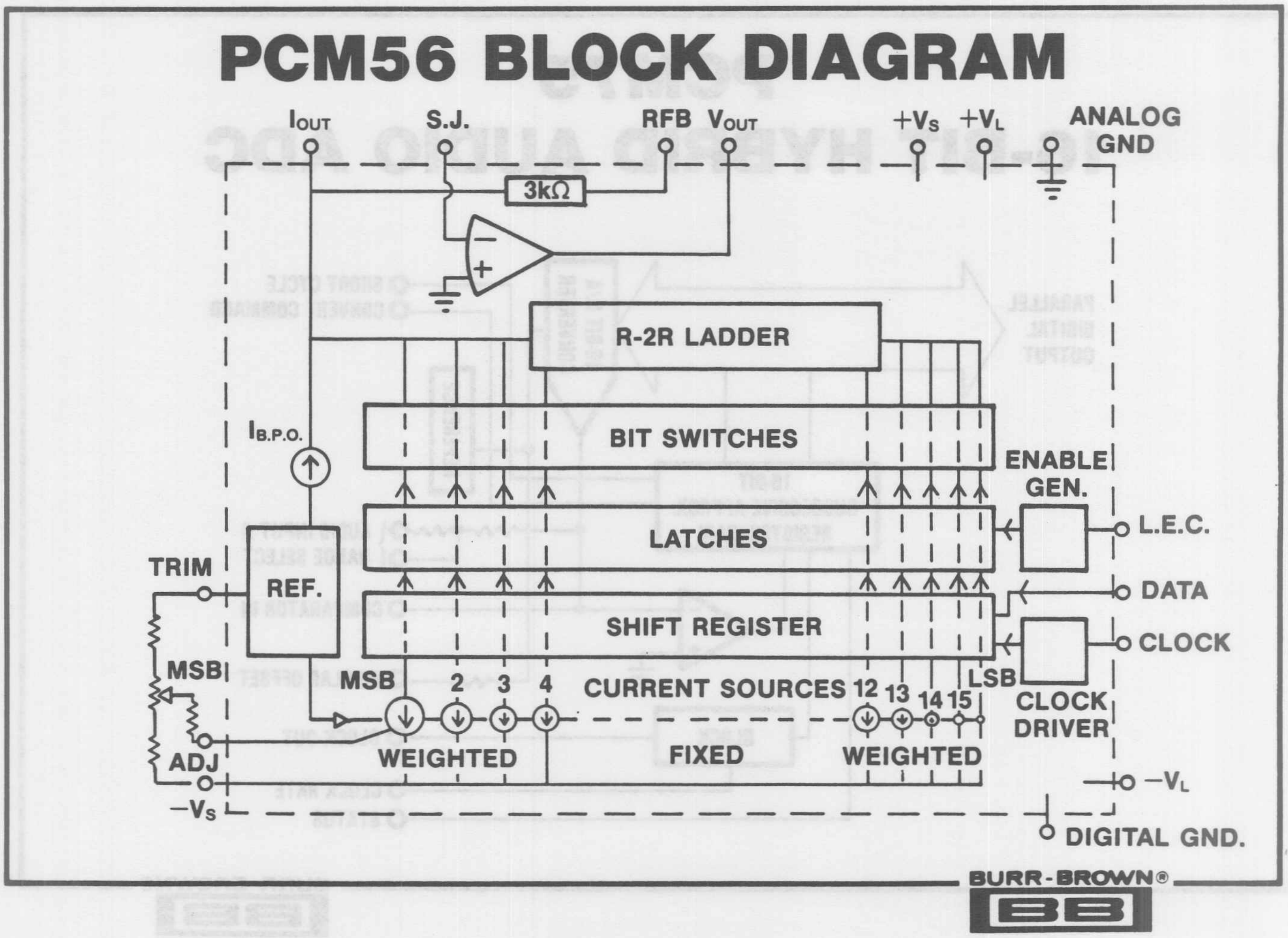
159 The PCM75 is a 16-bit A/D converter specified for audio applications.

FEATURES: - 16-bit resolution - 17 us conversion time - 0.004% THD at full scale input - parallel and serial outputs



160 The PCM56 is the latest PCM D/A design from Burr-Brown. It is our first PCM D/A with digital interface logic on the same chip. It has a serial input register and, of course, a D/A latch. All digital processors for new designs of compact disc players now have only a serial output.

PCM D/A
Other Applications

- **Waveform Generation**
  —Function Generators, Modems
- **Musical Instruments**
  —Synthesizers, Organs
- **Telecommunications Audio**
- **Audio Test Instruments**
- **Processors**
  —Speech, Music

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161 PCM D/A converters are being designed-in to several audio applications other than compact disc.

HIGH-SPEED
DATA CONVERSION PRODUCTS

BURR-BROWN®

162 Higher resolution converters, 12-bits and up, that are at the high speed end of the performance range require a mix of circuit device types that can be combined only by using hybrid circuit design and manufacturing technology.

High Speed Data Conversion Products

1. ADC803—12-bit, 1.5μs A/D
2. SHC803/804—300ns S/H
3. SHC5320—1.5μs S/H
4. MPC800/801—800ns to ±0.01% MULTIPLEXER
5. DAC63—12-bit, 35ns ECL D/A
6. DAC812—12-bit, 65ns TTL D/A
7. OPA600—100ns to ±0.01% OP AMP
8. OPH605—400ns to ±0.01% OP AMP

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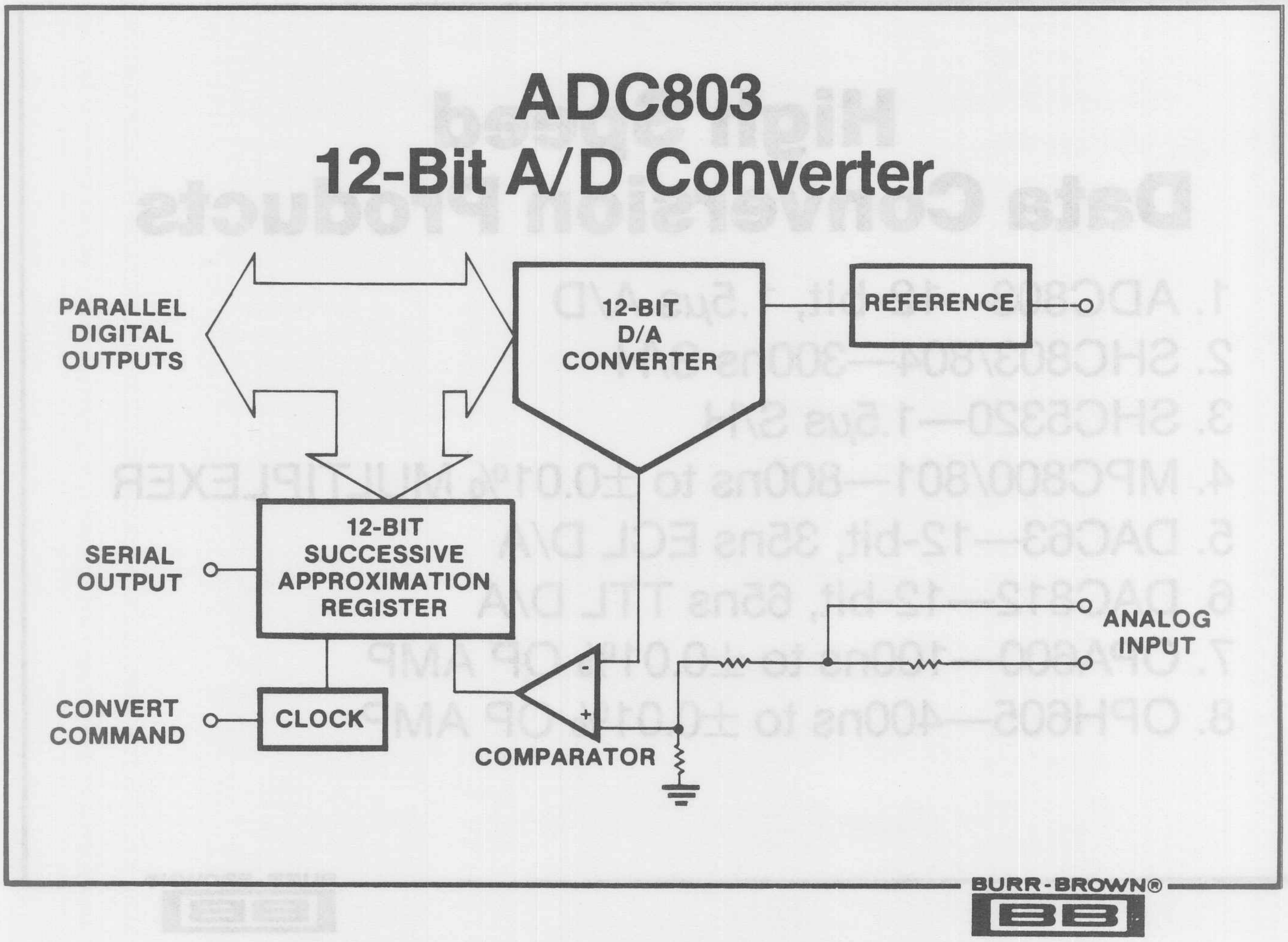
163 Burr-Brown's family of high speed converter products is listed here with a couple of companion op amps thrown in.



164 This popular model has proven itself to be the best choice for high performance 12-bit high speed applications.

FEATURES:

ADC803
- 1.5 us conversion time for 1/2 LSB linearity
- 1.0 us conversion time for NO MISSING CODES (NMC)
- EASY TO DRIVE ANALOG INPUT
- "S" grade NMC over MIL temp range
- 32-pin hermetically sealed DIP
- Separate analog and digital power supply returns
- Parallel and serial outputs
- Adjustable clock frequency

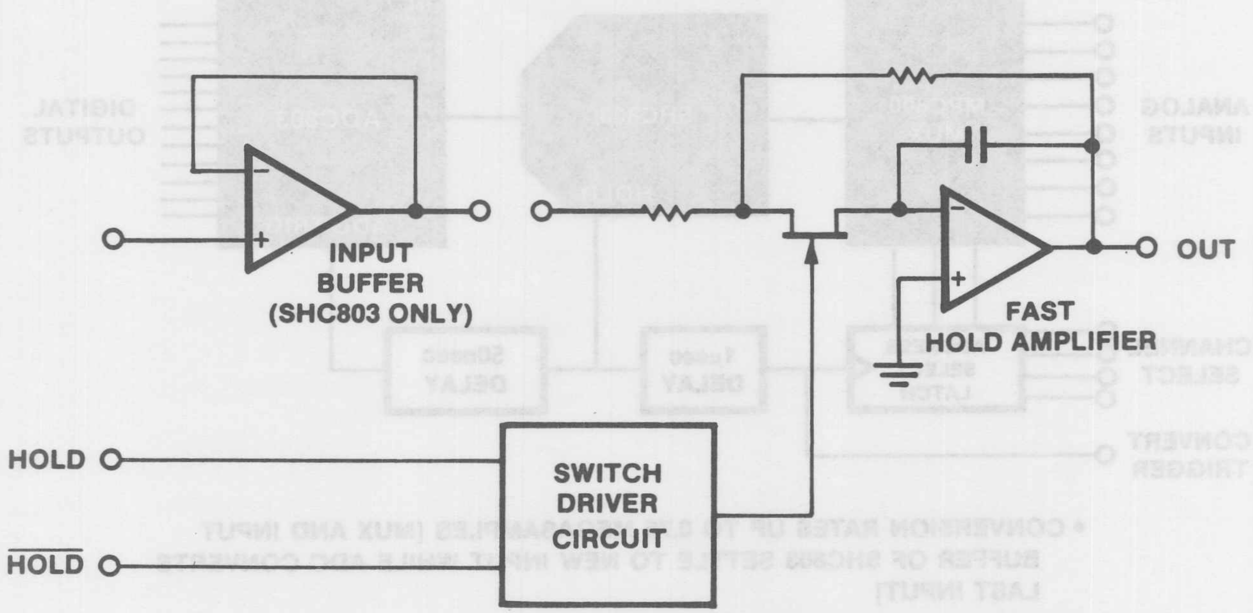
COMPANION PRODUCTS:

SAMPLE/HOLDS
SHC803 350ns Aq. Time (input buffer amplifier)
SHC804 350ns Aq. Time SHC5320 1.5us Aq. Time
MULTIPLEXERS
MPC800 8-ch. single ended / 4-ch. differential
MPC801 16-ch. single ended / 8-ch. differential
OP AMPS
OPA600 125 ns settling time to +-0.01%

REFERENCES:

Burr-Brown Application Note: AN-133, "Dynamic Tests for A/D converter Performance", October 1985.

SHC803/SHC804
HIGH-SPEED SAMPLE/HOLD



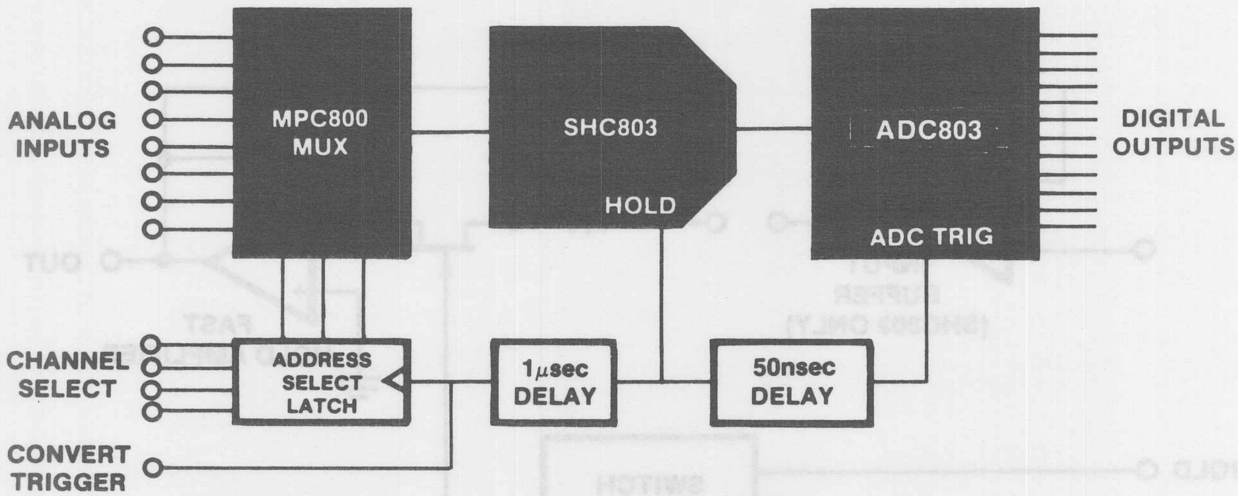
165 The SHC803 and SHC804 are companion sample-holds for the high speed ADC family. The SHC803 includes an input buffer that can be driven directly from a multiplexer such as the MPC800 or MPC801.

FEATURES:
- 350 ns full scale ACQUISITION TIME
- 20 ps APERTURE UNCERTAINTY
- +-10V input
- +-10V, 50mA output
- Power dissipation less than 800 mW
- 24-pin hermetic DIP

REFERENCE:

Burr-Brown Application Note: AN-147, "A waveform Digitizer for Dynamic Testing of High-speed Data Conversion Components", July, 1986.

Multiple Channel High-Speed Data Acquisition System



- CONVERSION RATES UP TO 0.75 MEGASAMPLES [MUX AND INPUT BUFFER OF SHC803 SETTLE TO NEW INPUT WHILE ADC CONVERTS LAST INPUT]
- NO EXTERNAL BUFFER AMPS REQUIRED

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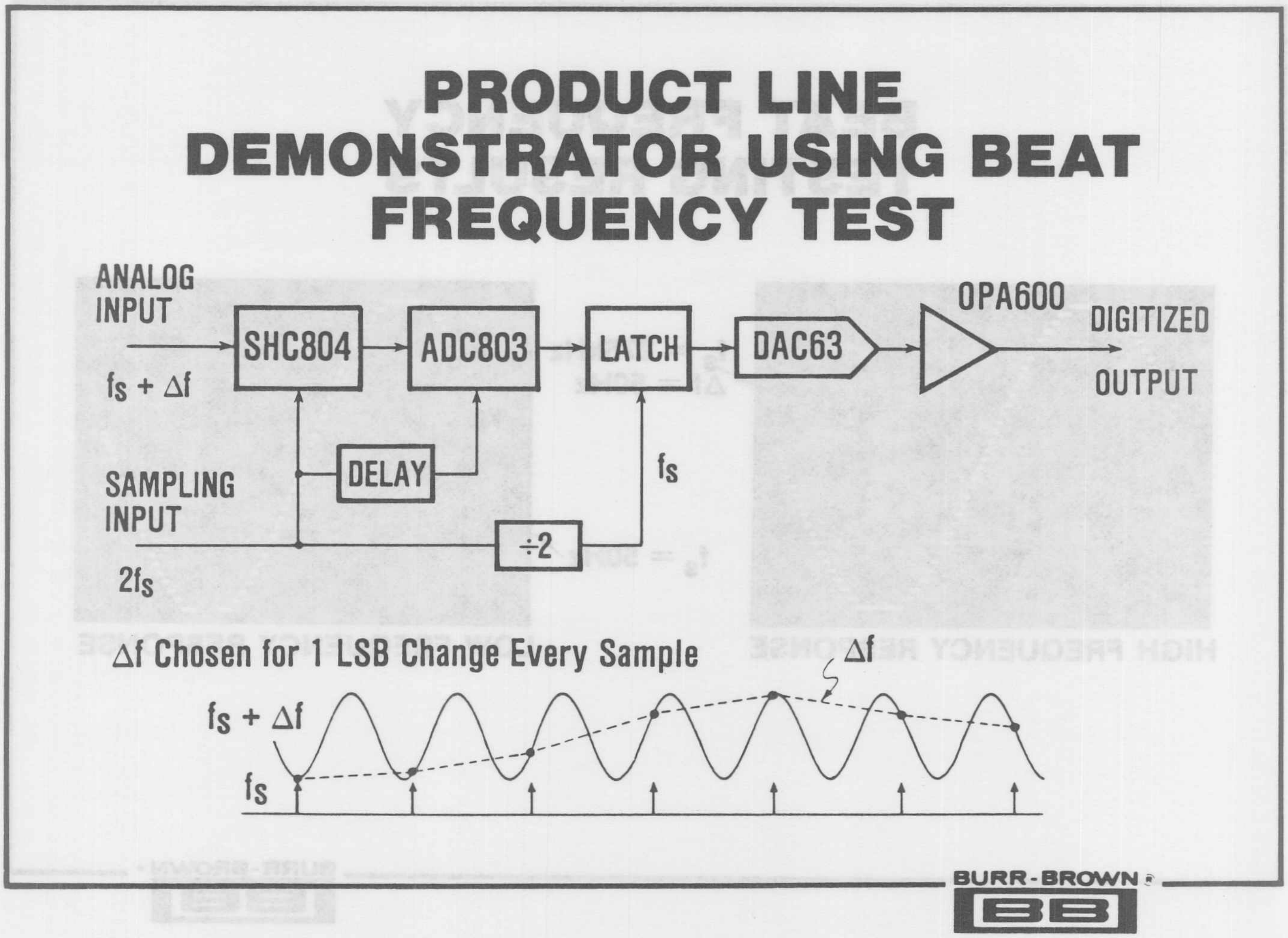
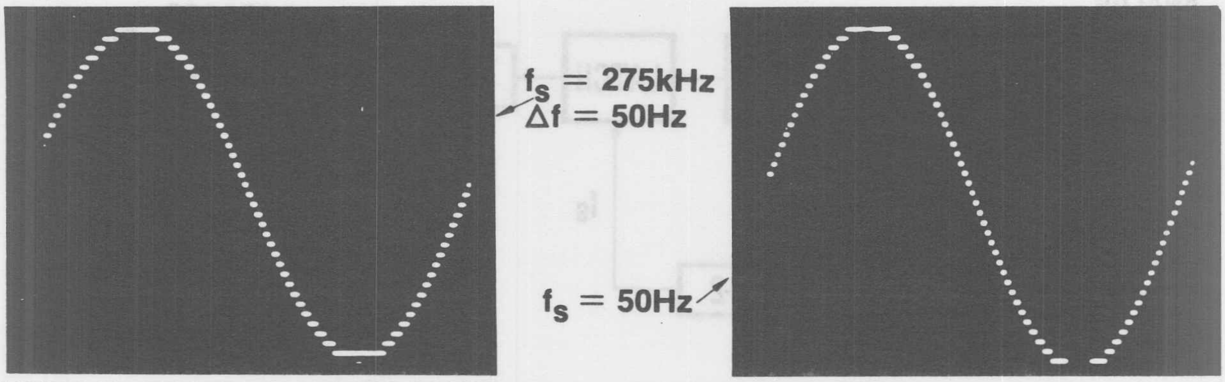
166 This block diagram illustrates how several high-speed devices can be put together to form a very high performance data collection system.

The speeds shown above are accomplished by increasing the clock of the ADC803 so that its conversion time is 1 us.



167 Burr-Brown uses demonstration boxes to show to customers several aspects of the performance of the ADC803. The test circuit used is called the beat frequency test. This test is a qualitative test that provides a quick, simple visual demonstration of A/D converter dynamic performance.

BEAT FREQUENCY TESTING RESULTS



HIGH FREQUENCY RESPONSE LOW FREQUENCY RESPONSE

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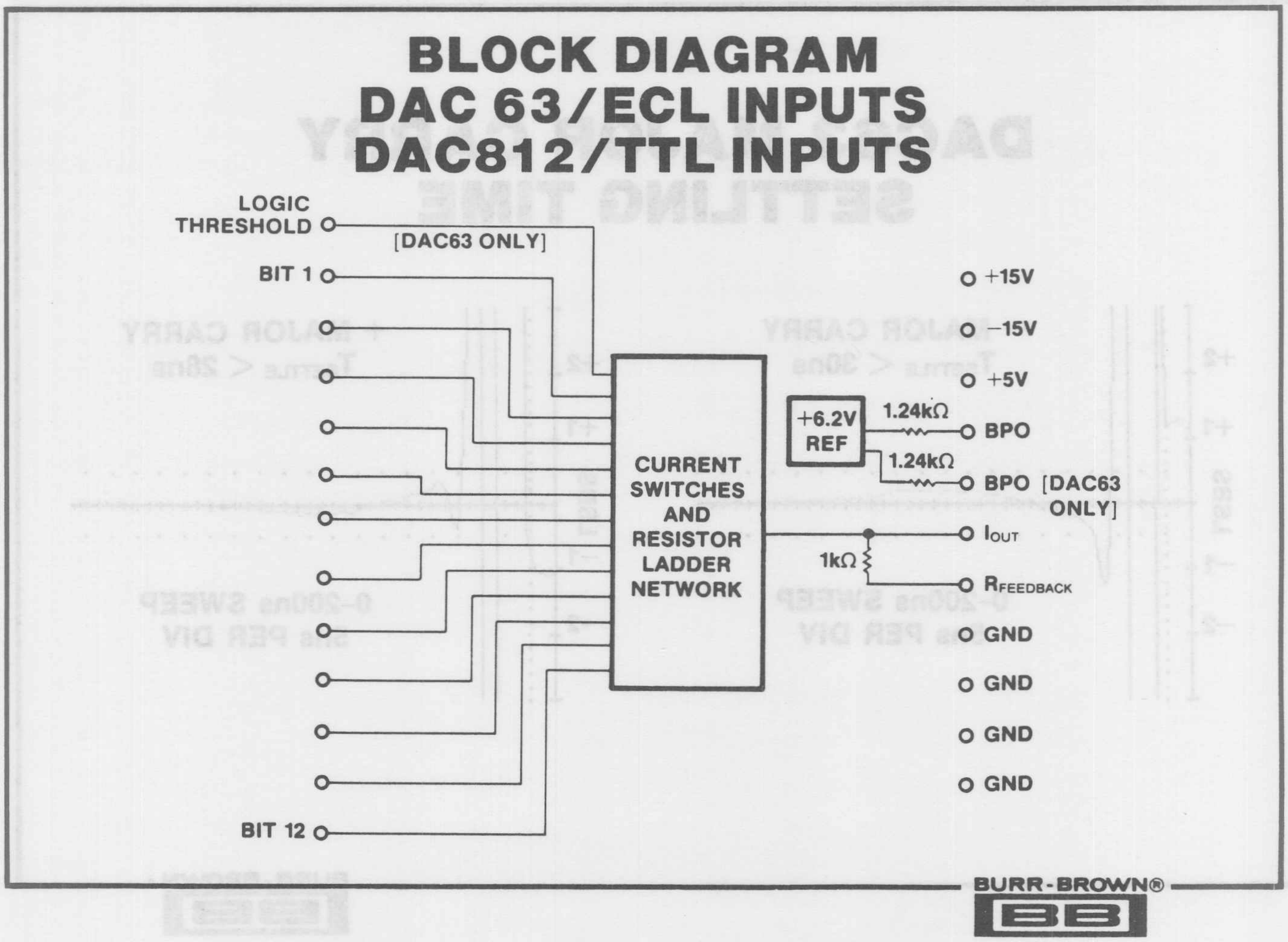
168 The input sinusoid is chosen to be a multiple of the sample frequency plus a small incremental frequency. Successive samples of the input waveform step slowly through the sine wave as a function of the small difference or beat frequency. Ideally, the multiplicative properties of sampling would yield a sine wave of the beat frequency displayed on a CRT. Error can be seen as deviations from a smooth sine function. Missing codes appear as local discontinuities in the sine wave. The oversize codes that accompany missing codes are seen as widening in the individual codes appearing on the sine wave.

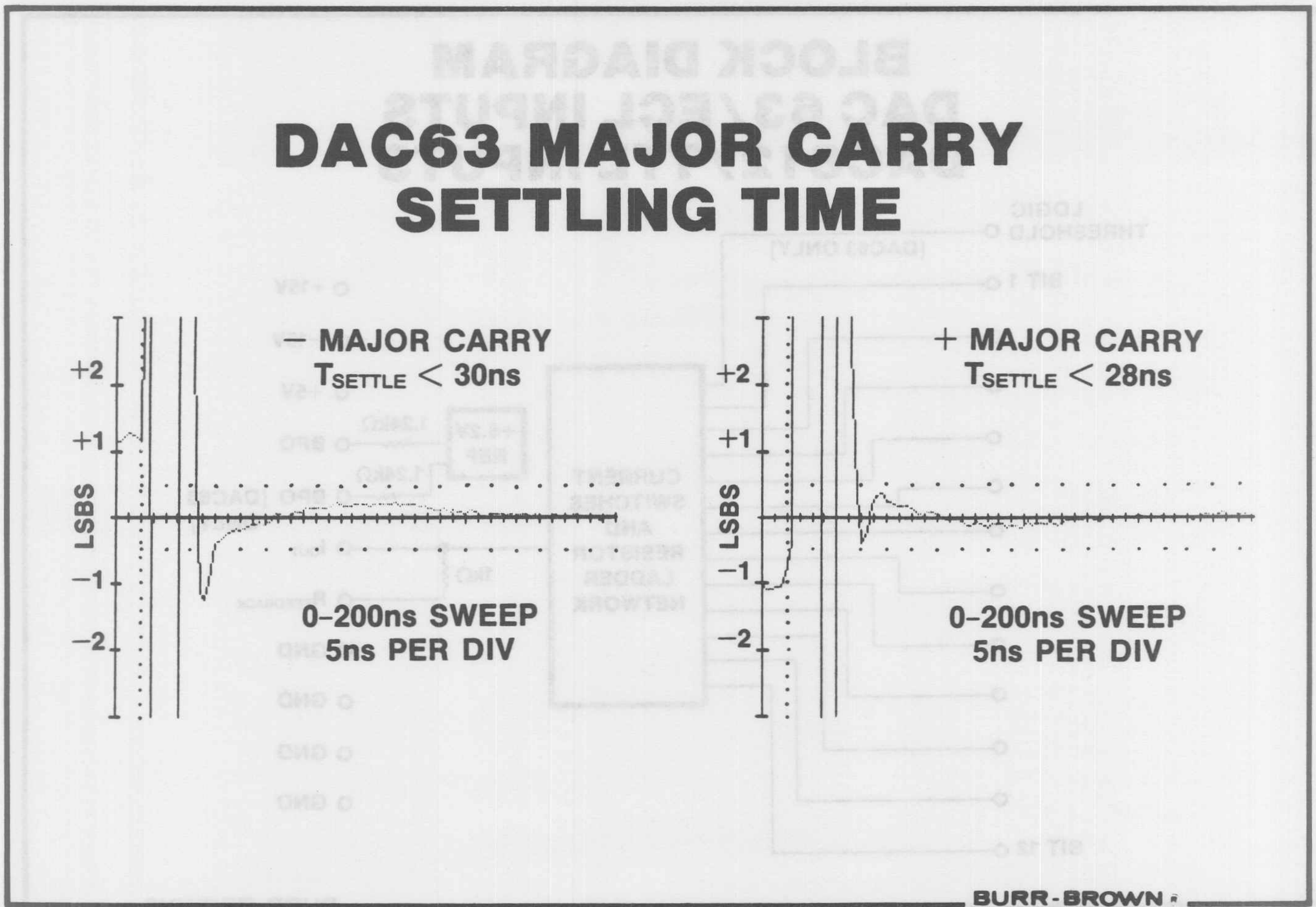
Shown here is the performance of the ADC803. As you can see, there is no detectable difference between a 50Hz or a 275kHz input sine wave.



169 The DAC63 and DAC812 are very fast settling current output 12-bit D/A converters useful for waveform generation, and CRT beam deflection applications.

FEATURES:
- 35 ns settling time (DAC63), ECL inputs
- 65 ns settling time (DAC812), TTL inputs
- Lowest glitch energy (DAC63), adjustable logic threshold
- Internally bypassed power supply lines to minimize settling time

COMPANION OUTPUT OP AMPS:
- OPA600
- OPA606

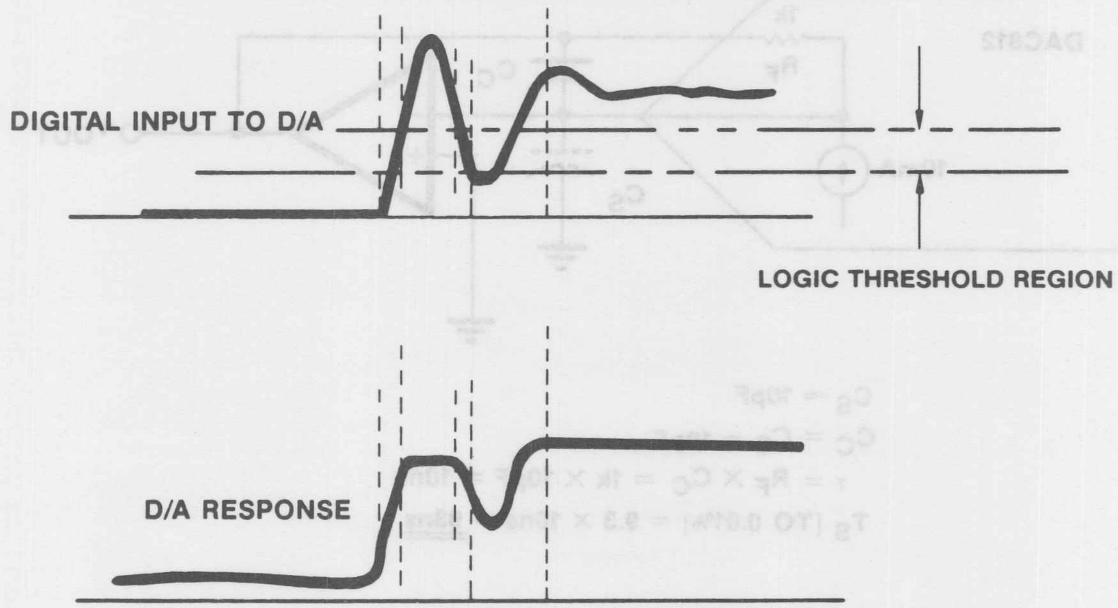


170 Shown here is the settling time response of the DAC63 current output D/A converter. Notice the glitch is large compared to an LSB. In fact, it is about 10 to 15 LSB high. Note that the net "glitch energy" (net area) is low. One graph is for a positive change, then other for a negative change.

The settling time was measured using the digitizing method described in the reference below.

REFERENCES: Burr-Brown Application Note: AN-147, "A waveform Digitizer for Dynamic Testing of High-speed Data Conversion Components", July, 1986.

NOISY D/A OUTPUT CAUSED BY RINGING OF DIGITAL INPUTS



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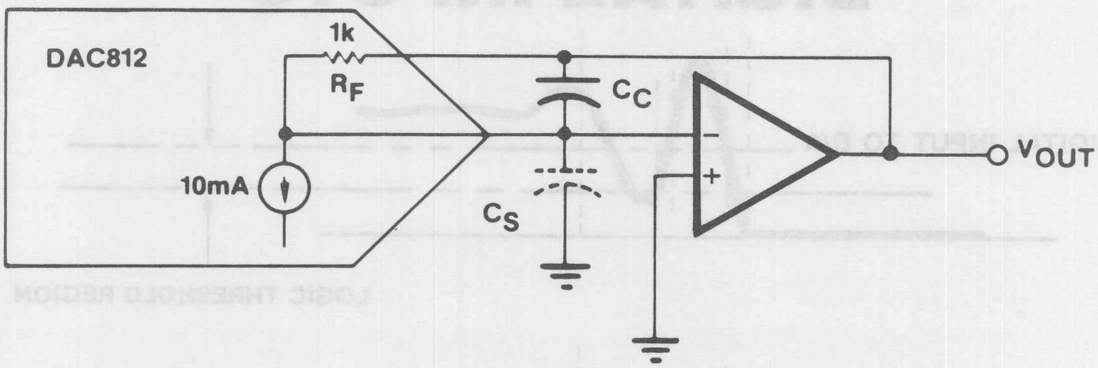
171 If digital input lines to high-speed D/A converter are somewhat long, the inputs to the D/A may ring during the digital transitions. These digital line driving situations can cause apparent settling time difficulties because the ringing may couple through to the D/A output.

ECL has a distinct advantage over TTL in these situations. This illustrates the importance of providing a clean digital drive to a D/A converter, especially high-speed types.

HOW TO IMPROVE SETTLING TIME



$$C_S \approx 10\text{pF}$$

$$C_C = C_S = 10\text{pF}$$

$$\tau = R_F \times C_C = 1\text{k} \times 10\text{pF} = 10\text{ns}$$

$$T_S\ [\text{TO } 0.01\%] = 9.3 \times 10\text{ns} = \underline{93\text{ns}}$$

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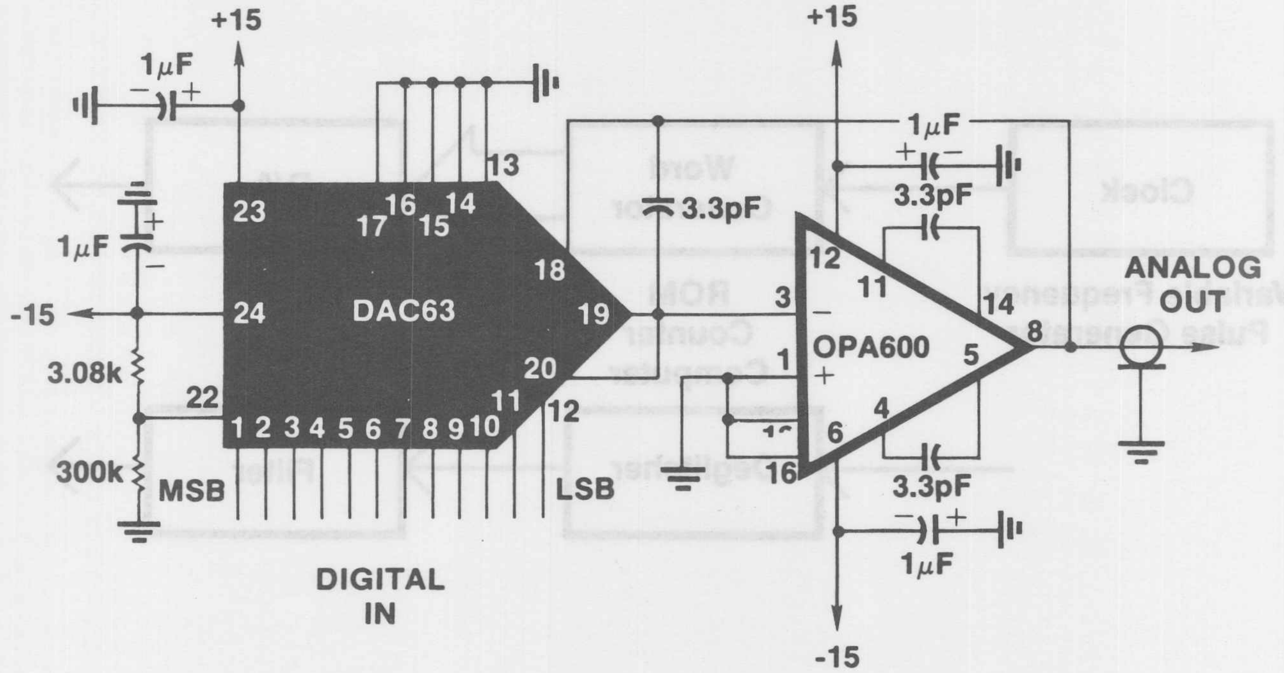
172 A high-speed D/A converter such as the DAC812 has an output current of 10mA so the feedback resistor is smaller by a factor of 5 compared to the general purpose converters such as DAC80 and the DAC811. In addition, the output capacitance of the D/A, Cs is smaller.

DAC812 (and DAC63) uses thin-film on sapphire to achieve this low capacitance. This is an example where the mixed technology approach using hybrid techniques can optimize performance.

12-BIT VOLTAGE OUTPUT D/A WITH 150nsec SETTLING TIME



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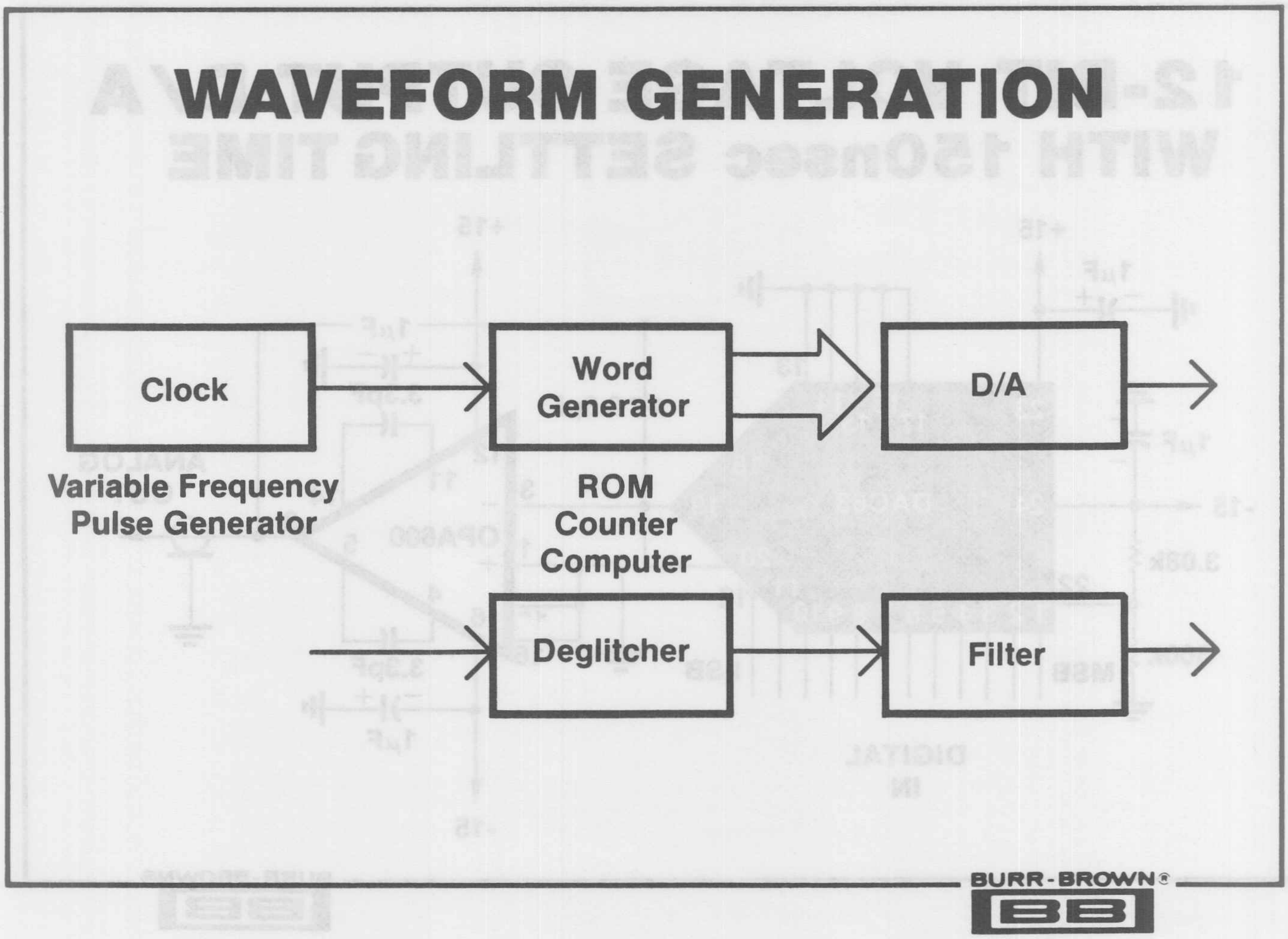
173 Example of a very fast settling DAC63/OPA600 combination. Note the 3.3pF D/A output capacitance compensation capacitor between pins 18 and 19.



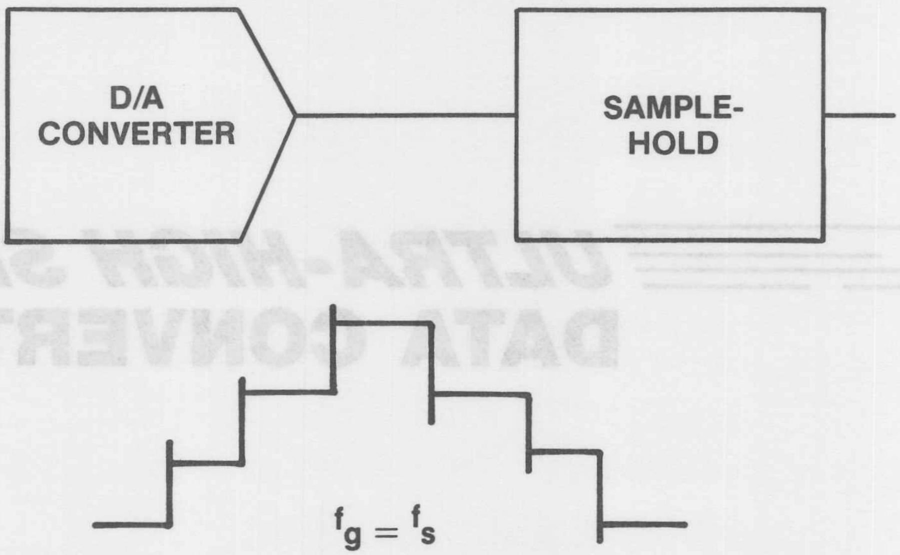
174 Many modern waveform generators whether they are stand alone instruments or part of larger test systems use digital logic such as counters, ROM's or microprocessors to generate time functions in digital form and convert these words to analog form with a D/A converter.

High speed D/A converters such has the DAC63 or DAC812 are often used in this application.

In waveform generation applications a significant harmonic at the waveform periodic frequency could be generated, because the largest glitch occurs when the most significant bit switches on or off usually as the waveform passes through zero.

Linear filtering of glitches leads to badly distorted waveforms because the glitches have magnitudes that vary widely and do not occur at uniform intervals.

WAVEFORM GENERATION DEGLITCHING



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175 Often a sample-hold amplifier or a deglitcher circuit is used to suppress these major carry glitches. But the deglitcher itself has a switching spike and transient as it switches from SAMPLE to HOLD. What has been gained?

Deglitchers are designed for low TRACK-to-HOLD transient. So the D/A glitch at the MSB transition of the D/A converter will, indeed, be considerably reduced. But other glitches will be added to the waveform at all code transitions.

The harmonic content of these small glitches is now shifted to the data rate frequency of the waveform generator which is usually several multiples of the waveform periodic frequency. This is easily filtered.

Some fast D/A converters may not need a deglitcher. The PCM56 (digital audio D/A) does not use deglitchers in any compact disk applications. The MSB glitch is already low. All PCM56 dynamic specs are guaranteed without an output deglitcher.

ULTRA-HIGH SPEED DATA CONVERTERS

BURR-BROWN®

ADC600

- **12-bit resolution**
- **10 megasamples per second**
- **Contains sample-hold**
- **Characterized for DSP applications**
  (AC specifications)

BURR-BROWN

176A

ADC600 Characteristics

Resolution	12 bits
Analog input range	±1.25V
Input impedance	1.5MΩ
Integral linearity error	±.5LSB
Differential linearity error	±1.0LSB
Harmonic distortion	70dB below FS
Aperture uncertainty	±5ps
Input bandwidth	50MHz
Sampling Rate	DC to 10MHz
Power consumption	8.5W
Size	0.25 × 3.75 × 4.5 inches

BURR-BROWN®

177 ADC600 is a new ultra-high speed A/D converter from Burr-Brown. It converts at 10 megasample per second rate and has a self-contained sample hold. This is the smallest, lowest power, best performing 10 megasample per second 12-bit A/D converter on the market.

Applications include digital oscilloscopes, waveform analyzers, and radar signal processors. The ADC600 has a particularly clean spectral response and an excellent signal-to-noise ratio.

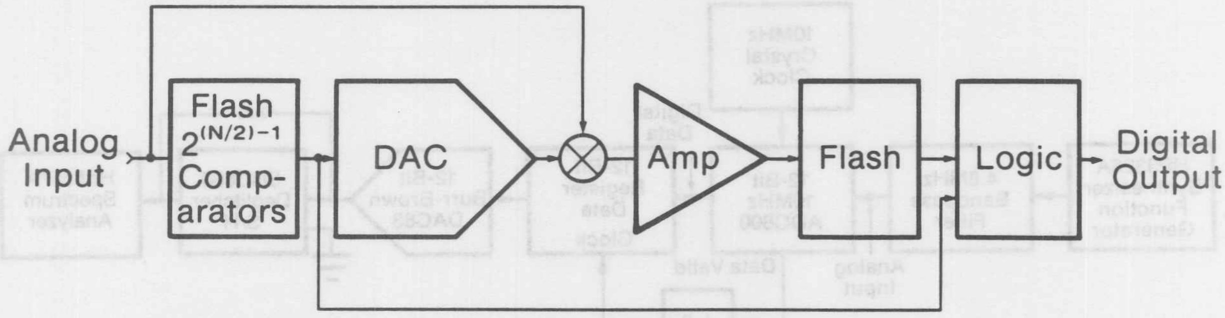
There are no external parts required. There are no trim potentiometers on the card and no "tweaks" are required for any sample frequency from DC to 10 megasamples per second.

REFERENCE:

Burr-Brown Application Note: AN-148, "Subranging High-speed Modular Analog-to-digital Converters", July, 1986.

Burr-Brown Application Note: AN-133, "Dynamic Tests for A/D Converter Performance", October, 1985.

Subranging ADC



$$\text{Conversion Time} = 2 \times \text{Flash} + \sqrt{\text{DAC}^2 + \text{Amp}^2 + \text{Logic}}$$

$$\text{Complexity} = 2 \times (\text{Comparator}) \times 2^{(N/2)-1} + \text{DAC} + \text{Amp} + \text{Logic}$$

BURR-BROWN

178 The ADC600 uses a subranging architecture to achieve ultra-high speed and 12-bit performance.

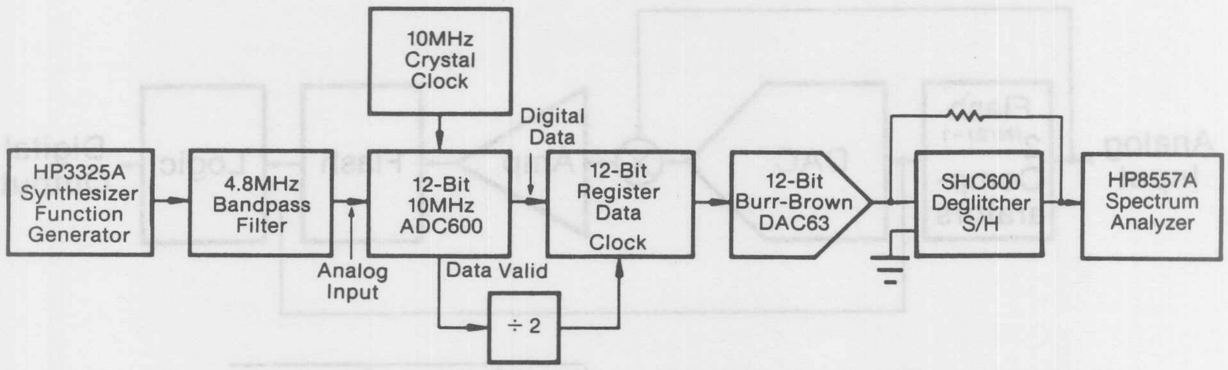
The analog signal is initially sent to a sample-hold (not shown) to reduce the aperture jitter of the A/D to 5 picoseconds. The output of the sample-hold is then sent to two circuits: a 7-bit flash encoder circuit and to a subtraction circuit.

The first flash encoder converts an initial coarse approximation of the input signal level. The output of the first encoder is converted back to analog form with an accurate D/A converter and subtracted from the input signal for further processing.

The result of the subtraction is amplified by a gain-of-32 amplifier to scale the difference to the proper level before being applied to the second flash encoder.

Once the data in each of the encoders has been latched it is sent to the digital error correction circuit to be assembled into the final 12-bit word.

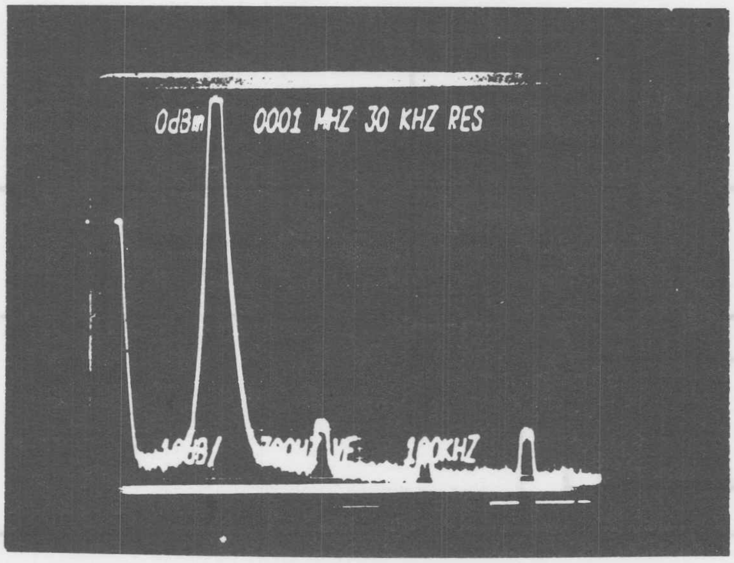
Block Diagram of Spectrum Analyzer Test



179 This block diagram illustrates the setup for harmonic distortion tests using an analog spectrum analyzer. Note the care taken to generate a pure sinewave. The spectrum analyzer must have a spurious free wide dynamic range.

The input test signal is set at 4.8 MHz to test the 10 Msps converter at close to the Nyquist rate. The ADC600 output was demodulated at a 5 MHz rate to provide a spectrum analyzer display with greater frequency resolution. With this "beat frequency" technique the effects of the D/A converter settling time and glitches are minimized.

Spectrum Analyzer Test Results



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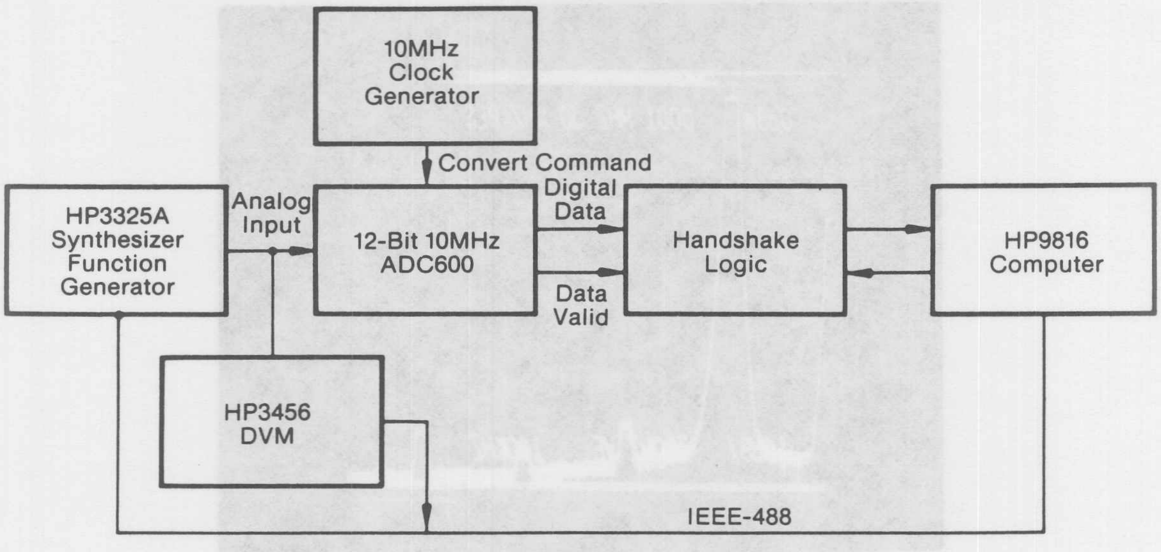
180 The difference frequency of 200kHz is displayed in place of the actual signal frequency of 4.8 MHz. Demodulating the signal at one-half the sample rate still maintains the correct relationship of the harmonics to the fundamental. Only the frequency has been shifted.

The harmonic generation of the A/D converter is estimated to be at least 70dB below the fundamental for a full-scale input signal.

Block Diagram of Histogram Test



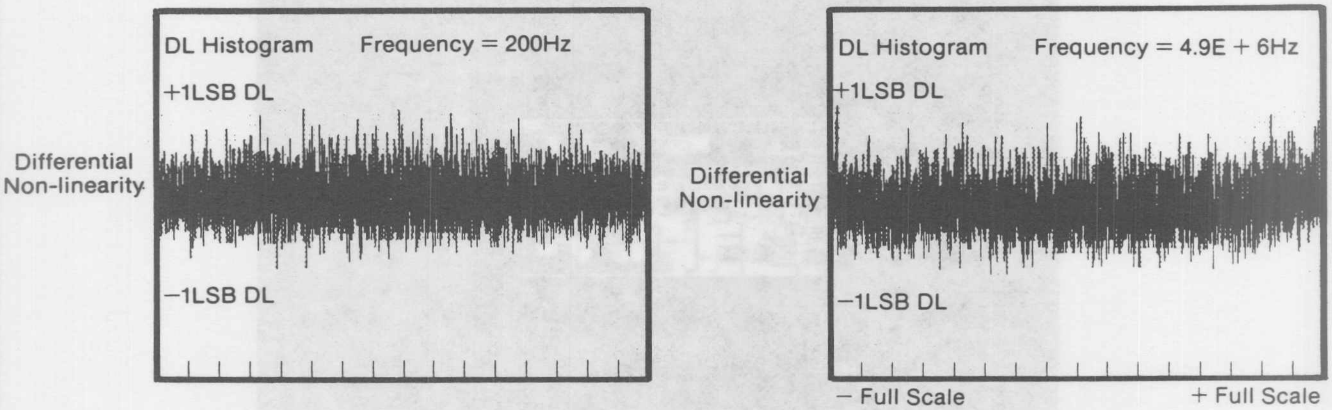
BURR-BROWN® BB

181 The block diagram of the setup used to characterize the ADC600's DIFFERENTIAL LINEARITY histogram is shown above.

Histogram testing is a useful performance indicator because the width of all the codes can rapidly be determined. The test system shown here conducts a 100,000-point test in two minutes. A more hardware based test setup would take about 15 seconds.

A sine-wave-based histogram test provides both a localized error description and some global description of the A/D. Using the histogram test, it is possible to obtain the differential nonlinearity of the A/D , to see whether any missing codes exist a the test frequency, and to get a measure of gain and offset at the test frequency. The histogram test provides the best information about individual code bin size at an arbitrary frequency.

Histogram Test Results



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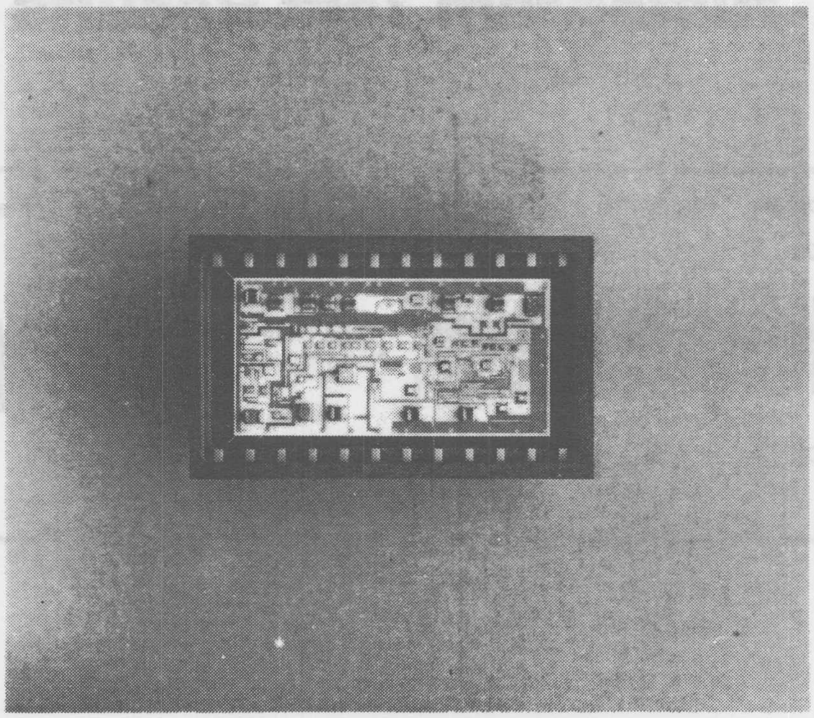
182 The histogram test was conducted at both 200 Hz and 4.9 MHz. The results are shown here. Note that both at 200 Hz and at 4.9 MHz, the typical DIFFERENTIAL LINEARITY ERROR is 0.5 LSB; the peak does not exceed 1 LSB. There are no missing codes.

This presentation shows a uniform distribution because the "U-shaped" distribution for the sinewave has been adjusted.

SHC600 Sample/Hold



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183 The SHC600 is a new ultra high speed sample hold useful for sampling systems requiring up to 12-bit performance.

SHC600 Characteristics

Acquisition time (2.5V step):	1%	20ns
	0.1%	30ns
	0.01%	40ns
Sample-to-hold settling (to 1mV)		10ns
Sample-to-hold transient		7mV
Aperture delay time		4ns
Aperture uncertainty		5ps
Small signal bandwidth		70MHz
Harmonic distortion (2Vp-p at 5MHz)		−70dB
Output current		40mA
Output Impedance		0.4Ω

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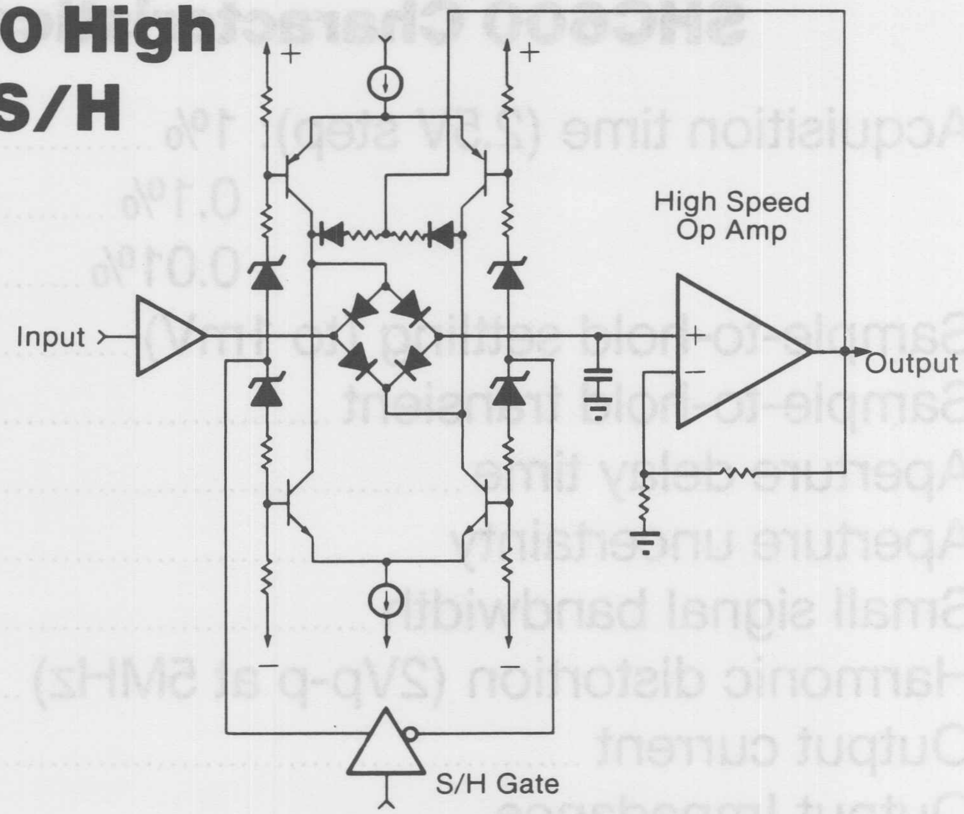
184 The important characteristics of the SHC600 to note are the INPUT BANDWIDTH, the APERTURE UNCERTAINTY and the HARMONIC DISTORTION.

Note also, that this is the only ultra-high speed S/H on the market with an acquisition time specified to 0.01%.

SHC600 High Speed S/H



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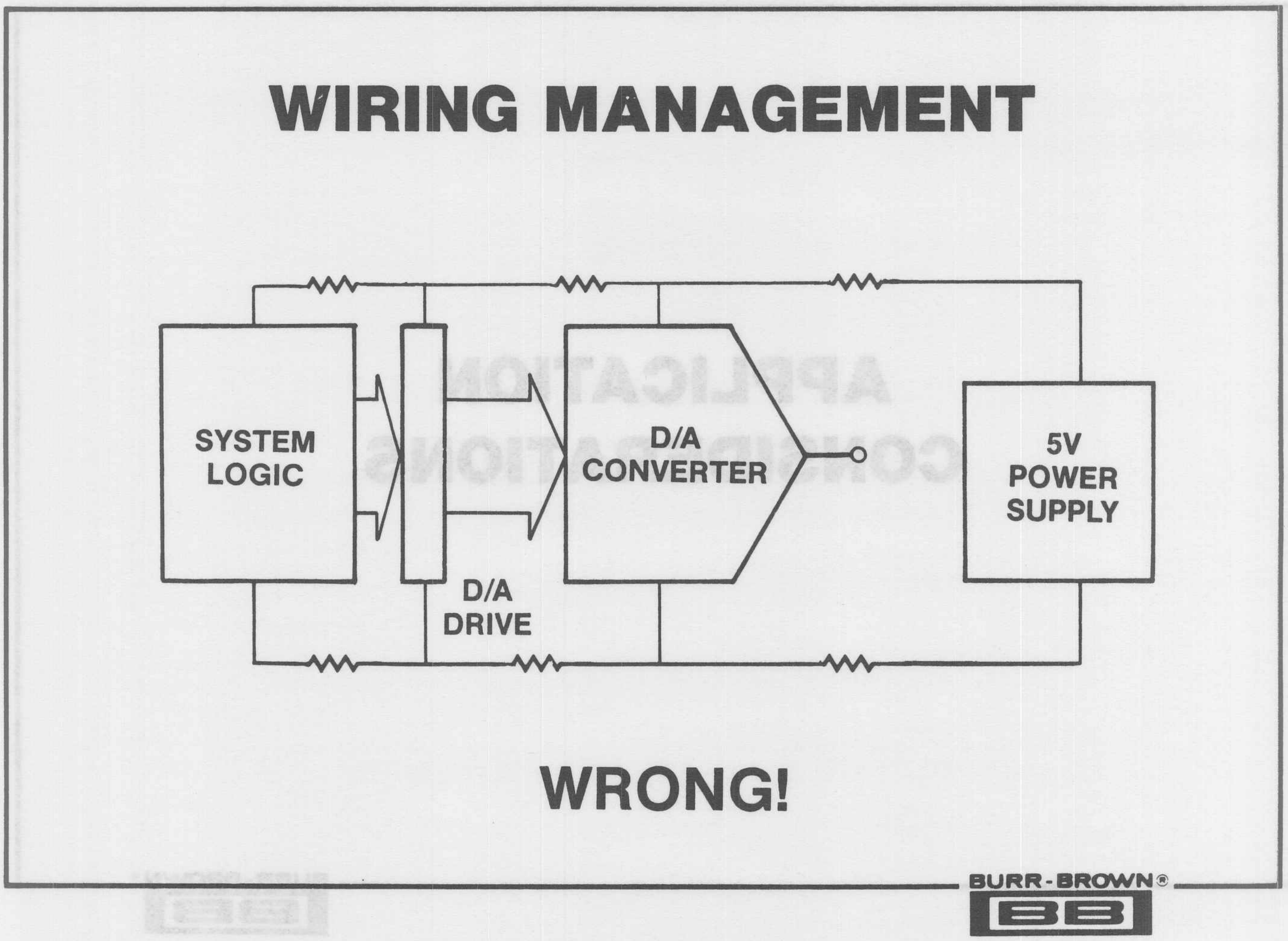
185 The diode bridge sampling switch offers the best solution to the conflicting requirements of accuracy and speed. Due to the fact that the capacitor is not in the feedback path of the output amplifier, the output amplifier does not drive the hold capacitor.

The closed loop output amplifier provides a maximum linearity error of +-0.01% with a low output impedance of 0.4 Ohms.

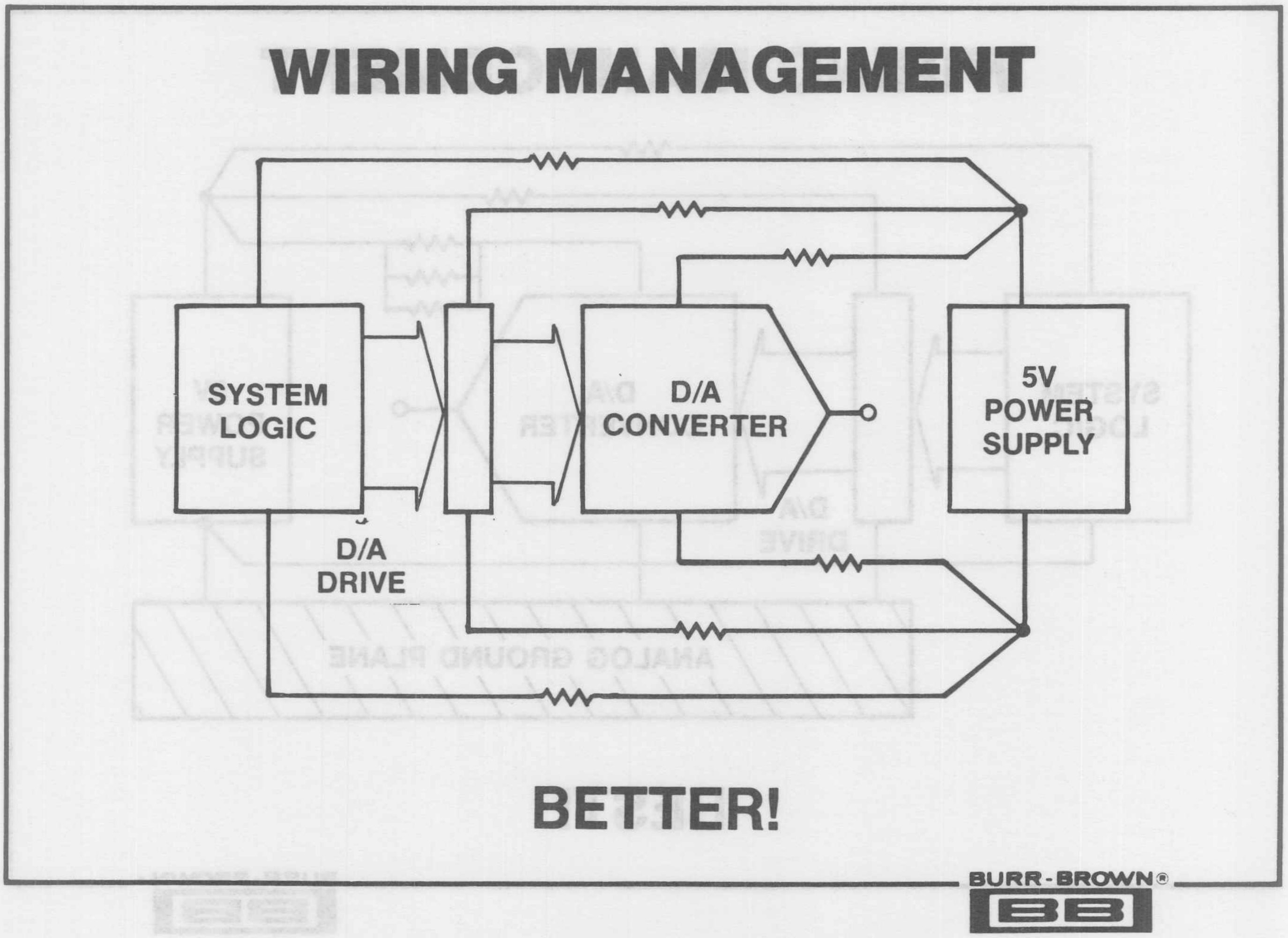
APPLICATION CONSIDERATIONS

BURR-BROWN®

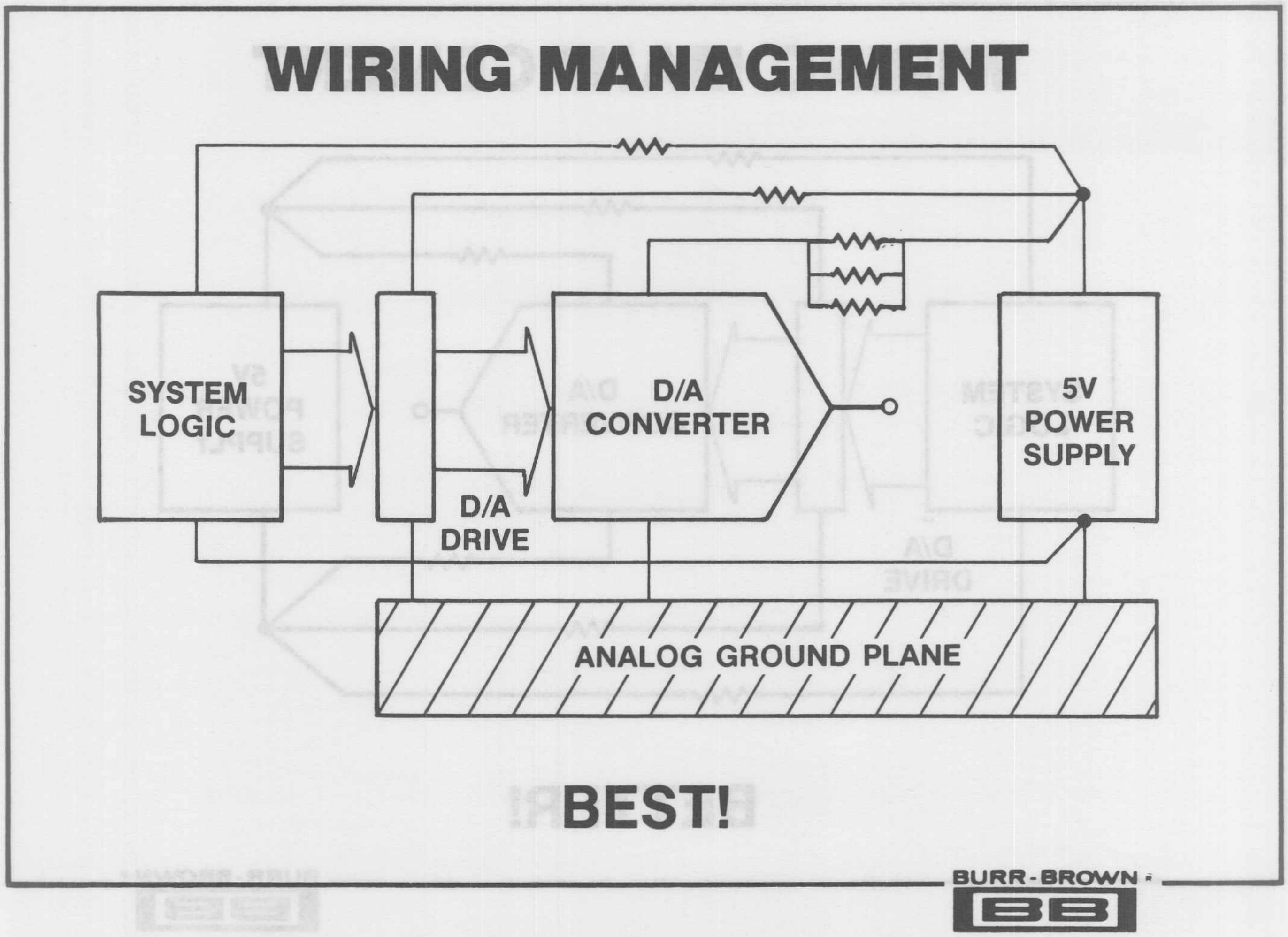


187 Many converters require a +5V logic supply and this supply is often provided by the system logic supply.

This slide shows that if the converter is inadvertently placed between the power source and the system logic spikes and dc levels are surely coupled into the converter and associated linear components.



188 This diagram shown better placement but there is still one better technique for handling the wiring for a converter.



189 A ground plane is the best solution to reducing noise coupling into sensitive converter circuits. High speed analog circuits should be sitting on top of a ground plane that covers every square inch of a board not in use for circuits or wiring. Even breadboards should be constructed using double-clad boards. It improves the designers chances of optimum performance.

Converter components designed for 12-bit and higher performance can easily be reduced to several bits less performance by careless power supply wiring and poor component placement.

BOARD LAYOUT CONSIDERATIONS

Converter components should be considered analog (not digital) components.

Use ground plane liberally. Breadboards should use ground plane as well. Avoid using hookup wire on the breadboard: Use copper pattern.

Use heavy power supply and COMMON (GROUND) wiring.

When passing through a connector, use every available spare pin for making power supply return connections and use some of the pins as a Faraday shield to separate the analog and digital returns.

Digital signals entering or leaving the layout should have minimum length to minimize crosstalk to analog wiring.

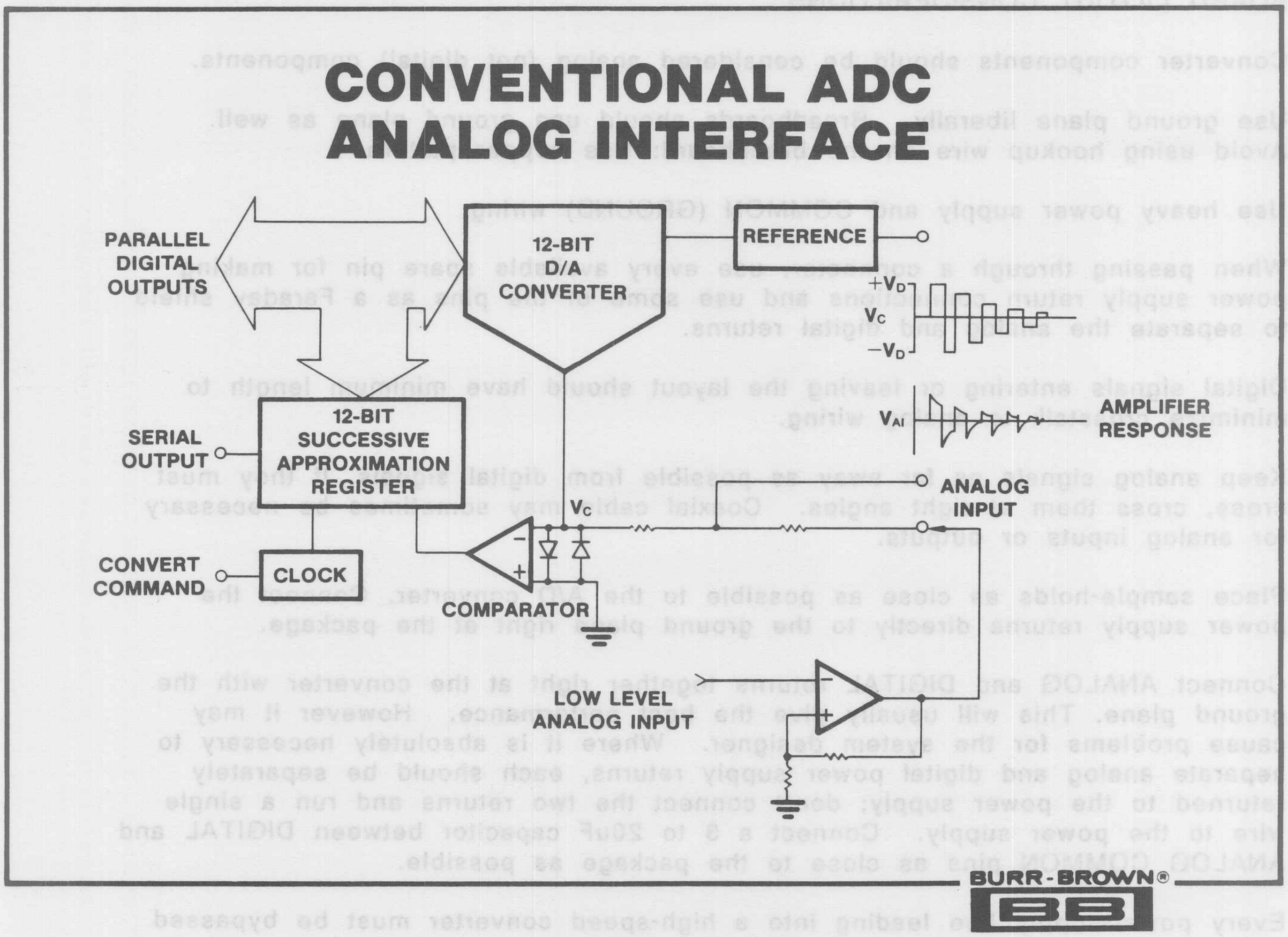
Keep analog signals as far away as possible from digital signals. If they must cross, cross them at right angles. Coaxial cable may sometimes be necessary for analog inputs or outputs.

Place sample-holds as close as possible to the A/D converter. Connect the power supply returns directly to the ground plane right at the package.

Connect ANALOG and DIGITAL returns together right at the converter with the ground plane. This will usually give the best performance. However it may cause problems for the system designer. Where it is absolutely necessary to separate analog and digital power supply returns, each should be separately returned to the power supply; don't connect the two returns and run a single wire to the power supply. Connect a 3 to 20uF capacitor between DIGITAL and ANALOG COMMON pins as close to the package as possible.

Every power-supply line leading into a high-speed converter must be bypassed to its ground return. The bypass capacitor should be as close to the converter package as possible. Use tantalum capacitors of 3 to 20 uF and be generous with the use of ceramic capacitors of 0.01 to 0.1 uF in the layout.

Linear power supplies are preferred. Switching power supply specifications may appear to indicate low noise output, but these specs are rms. The spikes generated in switchers may be hard to filter. Their high-frequency components may be extremely difficult to keep out of the power supply return system. If switchers must be used, their outputs must be carefully filtered and the power supply itself should be shielded and located as far away as from the analog circuits as possible.

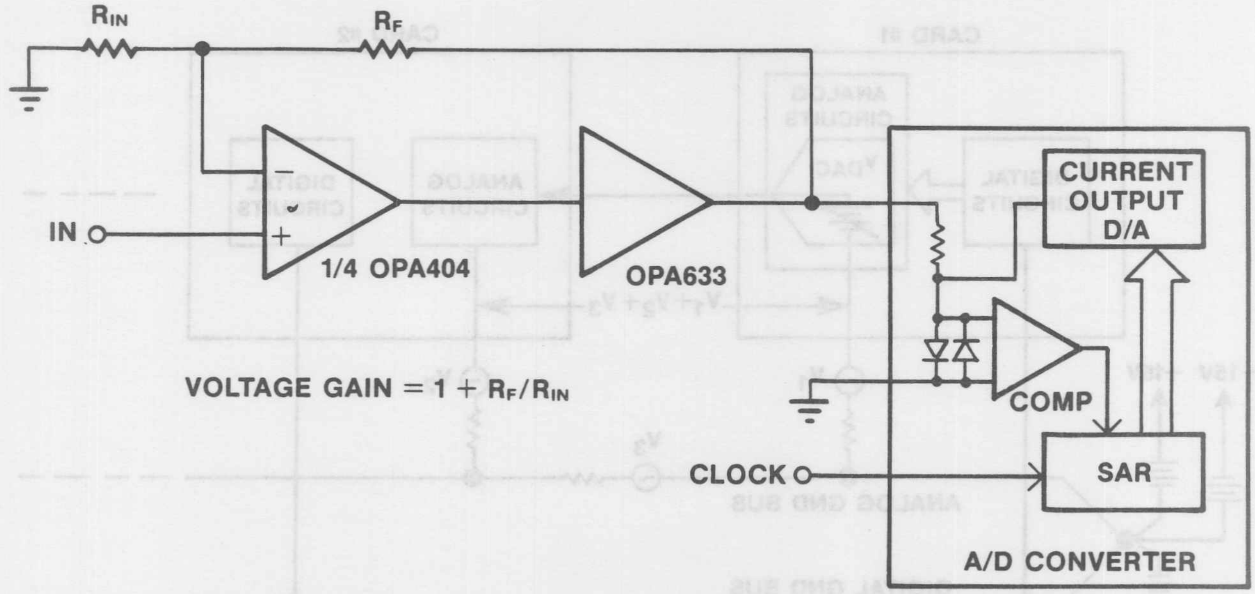


190 A successive approximation A/D converter has rapidly changing input currents during conversion. While this effect may not be significant at 12-bit converter accuracies it can have a detrimental effect in 14 to 16-bit applications.

The input current is compared to a trial current from the internal D/A. The comparison point is clamped but it may swing +/- several hundred millivolts. The output impedance of the device driving the A/D is very low due to the feedback connection of the high gain amplifiers usually used in sample-holds, instrumentation amplifiers or just op amps. But the loop gain of these amplifiers is lower at high frequencies. The output impedance of these devices may rise to 25 or 100 ohms or more.

This causes momentary gain errors that can appear as hysteresis, missing codes or at best poor linearity at the output of the A/D converter.

ADDING A FAST BUFFER



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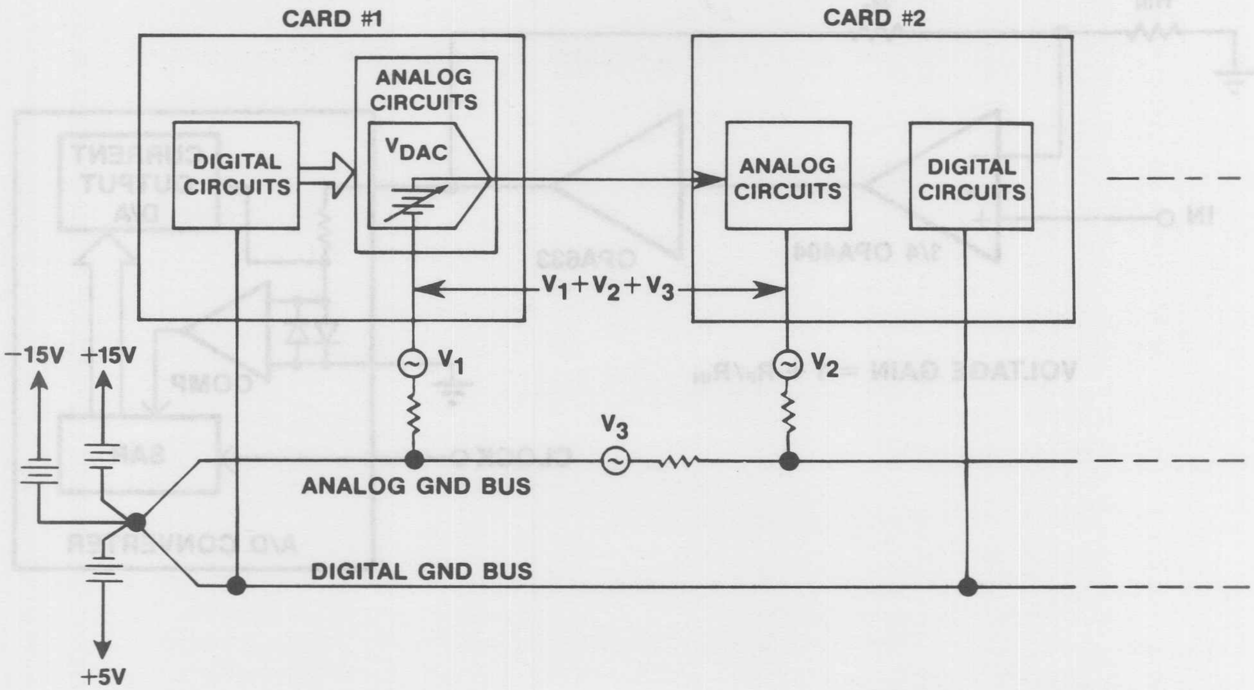
191 High resolution systems require precision amplifiers which, unfortunately, are likely to have low-bandwidth.

One solution is to use a wide-band but perhaps a less precise amplifier. Another solution is to add a high-speed unity-gain buffer stage to the output of the slower (but precision) amplifier is shown here.

GROUND MANAGEMENT



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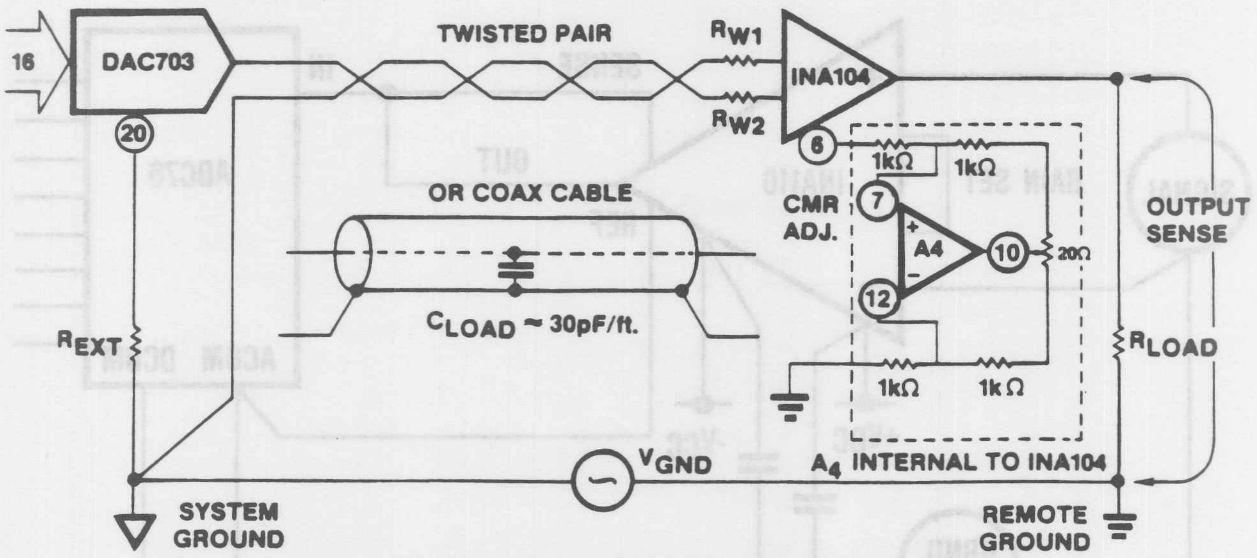
192 System wiring is fairly straight-forward when the D/A return and output load return sense share the same system ground potential. In many systems, however, these returns can be widely separated such that a potential difference exists between the D/A ground and the remote load. Since it is not always practical to reduce these ground drops to zero by using a large copper ground bus, another solution must be found.

PRESERVING ACCURACY WHEN DRIVING A REMOTE LOAD WITH DAC703



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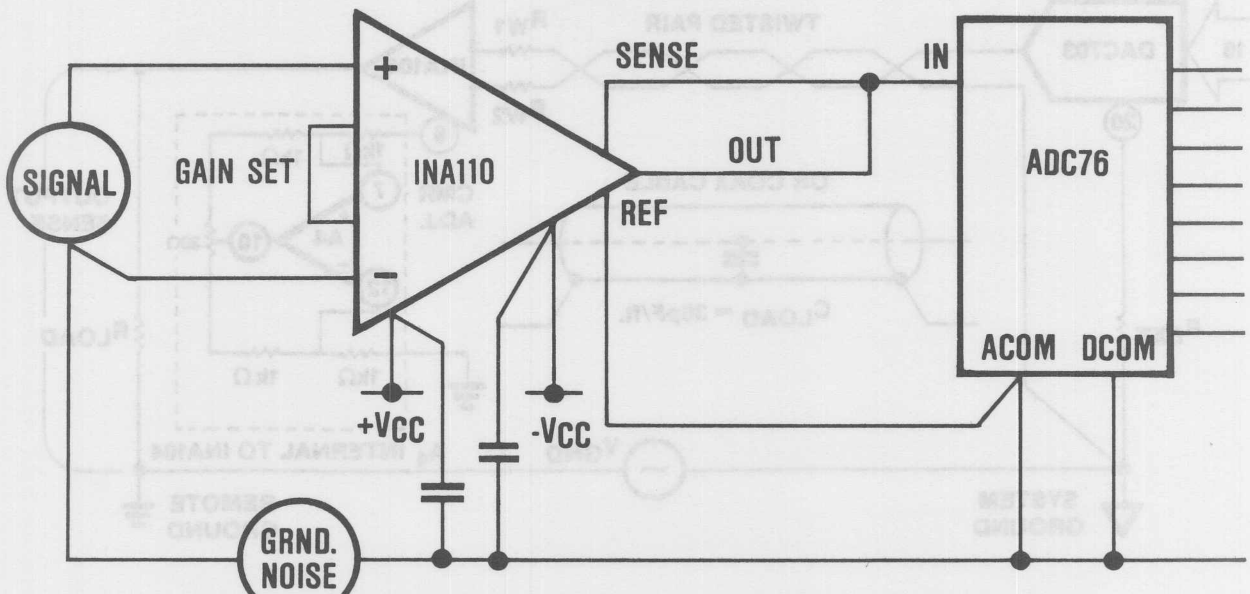
193 A method used to decouple common-mode signals generated in power supply return wiring is to use a unity gain instrumentation amplifier to reject the noise. This permits only the D/A output signal to appear across the load. By using the uncommitted amplifier inside the INA104 as a CMR adjust, the effect of mismatch in the writing resistance can also be removed.

In addition the DAC700 family of D/A converters has a power supply return whose change of current over all codes is less than 20 microamperes.

INSTRUMENTATION AMPLIFIER SIMPLIFIES SIGNAL CONDITIONING FOR A/D CONVERTER



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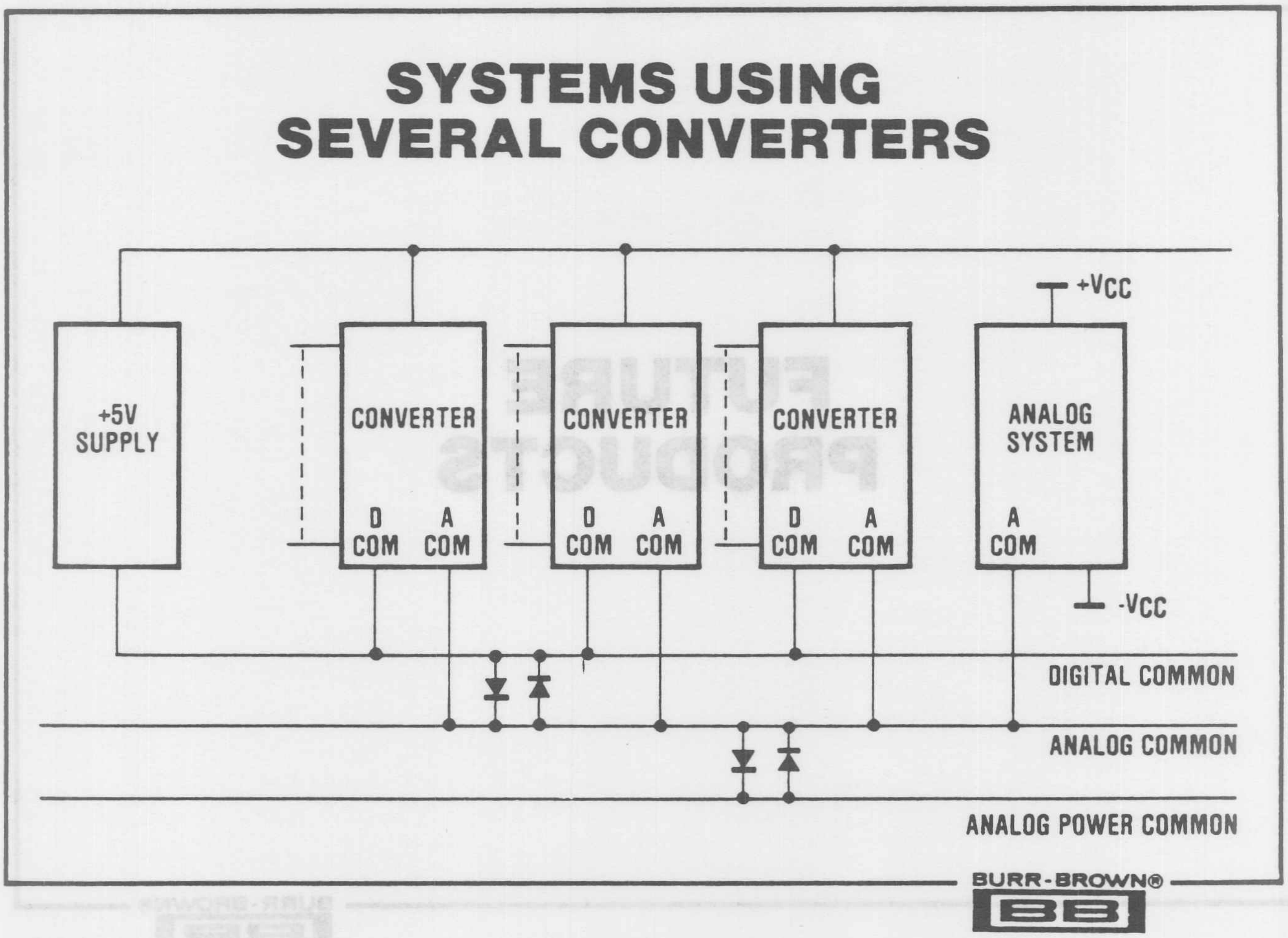
194 The previous slide illustrated how to translate signals between ground systems by using an instrumentation amplifier at the output of D/A converter. The same technique may be used at the input of a high-accuracy A/D converter.

The common mode rejection of the instrumentation amplifier is used to eliminate the effects of voltage differences between the signal COMMON and the A/D common. This circuit will provide much better common-mode rejection than using a simple op amp circuit.



195 In earlier discussions on wiring considerations, it was mentioned that optimum performance was usually obtained by connecting all power supply returns together at the ground plane under the converter components. If this is not possible, each return should be returned separately to the power supply.

In these cases, safety diodes should be added to systems where this common point is not on the same board. These diodes prevent large voltages from developing between common systems if the converters become separated from the key grounding point of the system.

High power analog signals may require a separate return to minimize IR drops in converter power supply return paths.

FUTURE PRODUCTS

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196 This section features some products that will be introduced in the near future.

DAC811JU

- DAC811 in SOIC
- 12-Bit Resolution
- Microprocessor Interface
- 28-Lead SOIC

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197 DAC811, the 12-bit converter with microprocessor interface will be available in plastic SOIC later this year. This will be the first complete D/A converter in this package.

Burr-Brown will have more components available in SOIC in the future.

DAC729

- **18-Bit Resolution**
- **16-Bit Linearity Error**
  ±0.00075% FSR at 25° C
  ±0.0015% FSR over temp
- **Precision 10V Reference**
  ±1ppm/°C Tempco
- **V_{OUT}, I_{OUT}**

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BB

198 DAC729 is another improvement in performance of high resolution D/A converters.

The architecture of this hybrid design optimizes the environment for a new 18-bit D/A converter chip. The reference and the output amplifier are not on the D/A converter chip. This permits optimization for noise and thermal stability.

This converter is designed to replace older modular converters and less stable 16-bit linear hybrid converters on the market.

The DAC729 is ideal for a reference D/A in test instruments and analytical instruments.

DAC725

- Dual 16-Bit Resolution
- ±0.003% FSR Linearity Error
- 8-Bit Port Interface
- Plastic and Ceramic DIP

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199 DAC725 is a dual 16-bit D/A converter in a 28-pin package. It has an 8-bit port with full bus interface logic.

This is essentially a dual DAC709. It will be available in ceramic and plastic using a new method for molding multichip hybrids in plastic.

INTRODUCTION: 2nd Quarter 1987

ADC700

- 16-Bit Resolution
- 17μs Conversion Time
- Extra Output Latch
- 8-Bit Port
- 28-Pin DIP

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200 ADC700 will be a new 16-bit 17us A/D converter in a 28-pin package. An interesting feature of the logic in this converter is that an additional latch has been added to increase the flexibility of interfacing to a microprocessor buss. This latch permits the user to read the data during the next conversion. This design also will have very low noise.

INTRODUCTION: 3rd Quarter 1987

DIE

ADC80KD	12-bit, 25μs; A/D
DAC80KD-V	12-bit, V_{OUT}; D/A
DAC811JD	12-bit, V_{OUT}, MD interface; D/A
DAC7541KD	12-bit, V_{OUT}, μp interface; D/A
DAC7700KD	16-bit, I_{OUT}; D/A
DAC7701KD	16-bit, V_{OUT}; D/A

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201 Burr-Brown monolithic converter products are also available in die form. Note that we have a single chip 12-bit A/D converter.